

THE RICE INSTITUTE

STRENGTH CHARACTERISTICS OF ROCK SAMPLES  
UNDER HYDROSTATIC PRESSURE

by

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## INTRODUCTION

In the never-ending search of the oil industry for new sources of oil, numerous holes must be bored into the surface of the earth. In some instances, holes as deep as 20,000 feet have been drilled. In order to keep pace with the constantly increasing demand for petroleum and petroleum products, the oil industry has had to devise new and better methods to penetrate into the crust of the earth in the search for oil.

Perhaps the most fundamental problem encountered in this accelerated program of discovery and exploitation is that of improvement of the tools and techniques with which holes are drilled. Ultimately, oil production is closely related to the number of holes drilled. Thus, in order to achieve higher production, it appears that faster penetration rates of drilling tools through the various formations encountered are necessary.

It has been known for many years that laboratory drilling tests on rocks did not agree with field results even when the formations were known to be the same. Although a number of variables could have contributed to this result, it was generally felt that pressure exerted upon the formation by the fluid column above it must have an important effect. Thus, a bit which performs quite well in the laboratory under atmospheric conditions may prove to be grossly uneconomical in the field under practical conditions.

This paper will deal with a study made to determine the specific effects of hydrostatic pressure upon the strength characteristics of various rock formations.

A review of the manner in which oil wells are drilled will assist in an understanding of the problem. Most modern day drilling of oil wells is accomplished by the rotation of a rock bit upon the formations which are to be penetrated. The bit consists of two or more conically shaped cutters, generally equipped with wedge-shaped teeth, mounted on bearings on a bit head. The bit is connected, by means of threaded connections, to a series of thick-walled pipes, called drill collars. The collars, which are part of the so-called drill string, serve to supply weight to the bit. Their length is usually 30 feet. Immediately above the drill collars, drill pipes, which are thin-walled tubes approximately 30 or 40 feet long, are used. Generally, a sufficient number of drill collars are used so that all of the drill pipe is in tension, that is, none of the weight of the thin-walled pipe is utilized to supply weight to the bit. The drill pipe is connected at the upper end to a member called a kelly. As drilling progresses, the kelly, which is square on the outside, moves vertically through the rotary table which applies the torque to the drill string. A drilling fluid is introduced into the top of the drill string through a hose and swivel assembly which is located immediately above the kelly.

The entire string is suspended from a derrick by a block and cable arrangement. Weight on the bit is varied as desired by allowing more or less of the drill string weight to be suspended by the block and cable assembly.

As the bit progresses into the formation, cuttings are produced. Efficient drilling demands that these cuttings be quickly removed so that the bit cutters always attack virgin formation rather than the cuttings. Removal of the cuttings is accomplished by means of the fluid which is circulated down through the drill string, through the bit, and back to the top of the hole in the annulus between the pipe and the wall of the hole. Thus the portion of the hole not occupied by drill stem is always filled with the drilling fluid. The long fluid column, in addition to removing the cuttings, also serves to contain excessive gas pressures which may be encountered.

The fluid, commonly called "mud", usually consists of a water or oil emulsion base fluid combined with solid additives in carefully controlled proportions. These additives serve to increase the weight of the mud, a property desirable from the standpoint of containing high gas pressures. Muds weighing twice as much as water are commonly used. A hydrostatic pressure is exerted by the long fluid column on the surface of the formation being drilled. In a well 17,000 feet deep, and using a mud twice as heavy as water, the hydrostatic pressure exerted

by the fluid at the bottom of the well would be approximately 15,000 psi.

The pressure exerted by the fluid column on the surface of the formation being drilled is not the only stress to which it is exposed. The complete stress picture at the bottom of the oil well hole is difficult indeed to analyze. The state of stress of the material surrounding the bottom of the hole as determined by overburden must be considered. Discontinuity stresses resulting from the intersection of the wall and the bottom of the hole should be considered, if they exist. The fact that the bottom of the hole is not plane, but consists of many small ridges and depressions formed by the rock bit teeth, should be given consideration. In view of the many unknown factors involved, it appears at present that only a qualitative analysis may be made. Jones<sup>9\*</sup>, in making an analysis of the stress conditions on the bottom of the hole, greatly simplifies the situation, but arrives at the conclusion that the assumption of a hydrostatic state of stress at the center portion of the bottom surface is justifiable. Other investigators are currently endeavoring to determine experimentally the state of stress on the bottom of a hole loaded hydrostatically. Results are not yet available.

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\* Numbers denote items in the Bibliography on  
Page 38.



Rock bit teeth act as penetrators in applying a differential load to the formation being drilled. This is a dynamic loading situation. It is felt, however, that knowledge of the static strength characteristics of rock formations must first be obtained before the dynamic situation may be analyzed.

Previous experimental investigations have shown that rock samples undergo marked changes in strength characteristics when removed from their natural environments in the subsurface of the earth and tested under atmospheric conditions. Generally, the samples support a much greater load when subjected to hydrostatic pressure and loaded differentially than when loaded under atmospheric conditions. Also, many formations exhibit a ductile type behaviour under conditions of high hydrostatic pressures whereas they are brittle under atmospheric conditions. The bulk of the previous work has been aimed at explanation of rock flow and displacement caused by geologic phenomena, and tests were accordingly carried out in high hydrostatic pressure ranges far exceeding the pressure range which is of interest ~~in~~ in the drilling of oil well holes. Very few tests have been conducted in the pressure range 0-15,000 psi.

In order to gain information relative to rock strength characteristics in this pressure range, tests on various types of rock samples were conducted by the author. It is the purpose of this paper to describe the tests

conducted and to present the results obtained. Results of tests on a number of formations commonly encountered in the drilling of oil wells will be presented.

SUMMARY OF PREVIOUS WORK ON ROCK SAMPLES  
EXPOSED TO HYDROSTATIC PRESSURES.

Probably the earliest work which was done in studying the effect of hydrostatic pressures upon rock strength and deformation characteristics was by F. D. Adams<sup>1</sup>. He demonstrated that rocks change their character under applied confining pressure so that they behave in a ductile rather than in a brittle manner. However, Adam's apparatus, in which the specimen was confined inside a steel jacket, had several defects. A load was placed on the ends of the steel-jacketed specimens so that, in expanding laterally, pressure between the specimen and the jacket was generated. In this scheme, it was impossible to measure the confining pressure because of friction between the jacket and the specimen. Also, the confining pressure changed as deformation continued, being zero at the beginning of the test. Too, major fractures of the specimens were prevented by the steel jacket.

Griggs<sup>4</sup> endeavored to overcome the defects of Adam's apparatus by using a liquid under pressure as the medium by which lateral pressure was applied to the specimen. An additional load was added to the ends of the specimen and the resulting deformation was measured directly. The method was essentially the same as that developed by Dr. P. W. Bridgman. The specimens were cylinders with a height of twice the diameter, following the practice of materials testing engineers. According to Griggs,

experience has shown that a height equal to twice the diameter is satisfactory, so that shear failures are not inhibited by the platens, and at the same time, buckling does not occur. In tests on Solenhofen limestone and on marble, specimens of both types exhibited brittle type failures at pressures up to 4,000 atmospheres. At 8,000 and 10,000 atmospheres, the stress-strain curves are characteristic of ductile materials showing a "yield point" and an increase in strength before rupture occurs.

In his compression tests, Griggs observed two types of failure, namely, "shear" and "tension". The former were inclined to the direction of compression at about  $45^{\circ}$ . These "shear" surfaces were commonly smooth, striated surfaces and showed granulation. They were lighter in color than the tension-crack surfaces because of fracturing and powdering of the crystals. The "tension" failures occurred on planes parallel to the axis of compression, and were generally clean cut with no evidence of powdering. Griggs observed that Luders lines developed on the surfaces of specimens slightly before rupture, and thus concluded that shearing failure was the first to occur. As a result of shearing, wedges were formed which acted to produce the longitudinal splitting, or tension, failures. He showed that every tension crack formed had a well-developed shear wedge associated with it. Griggs observed that if his conclusion concerning the tension failures were correct, then it would be expected

that their formation would be inhibited by confining pressure. He assumed that the liquid has no access to the point of the wedge, and states that the effective tension at the point of the wedge would be equal to the total resolved "tensile" force minus the force due to the confining pressure. Griggs noted, at higher confining pressures, that fewer tension cracks were formed, but also made the observation that some were formed even at 10,000 atmospheres confining pressure.

Tests made by Griggs indicated that the ultimate strength, defined as the final strength at the rupture point, was increased 1400 percent as the confining pressure was increased from 1 to 10,000 atmospheres. Adam's tests on marble, although not in agreement with Grigg's tests, also indicate a marked increase in strength with increase in confining pressure.

More recently, Handin<sup>8</sup> has performed tests in the 10,000 atmosphere pressure range upon Yule marble, anhydrite, and rock salt. A stress-strain curve for marble was obtained which agreed remarkably well with those obtained by Griggs under the same conditions.

It must be remembered that all of the aforementioned work was done in the high pressure range in attempts to arrive at an explanation of rock deformation and fracturing under very high pressures. Some tests were conducted up to 13,000 atmospheres, or the equivalent of about 28 miles deep in the earth. Of greater interest to those in the

oil well drilling industry are the characteristics which rock formations exhibit under pressures in the range 0 to 15,000 psi. Jones<sup>9</sup>, using equipment which was a modification of that used by Griggs<sup>4</sup>, made several compression tests on Carthage marble under pressures in the 0 to 15,000 psi. range and found that the strength increased approximately 264 percent as the lateral pressure was increased from 0 to 10,000 psi. A specimen tested at 10,000 psi exhibited ductile properties, while that at atmospheric pressure was characterized by a brittle type failure.

Recently, tests<sup>11</sup> on a large group of formations were made on typical foundation rocks. All rocks tested exhibited marked increase in strength with increasing confining pressure. These tests were made in the range of 0 to 1900 psi. confining pressure.

## EQUIPMENT USED IN STRENGTH TESTS

The pressure testing equipment used in the tests conducted by the author was that designed and built by Jones<sup>9</sup> and described in his paper. The design is based upon that of the apparatus used earlier by Griggs<sup>4</sup> in his high pressure work. Use of confining pressures lower than those used by Griggs permit certain simplifying modifications to be made, especially with respect to seals. The apparatus was designed for use in both compression and tension, or "extension", tests. However, it was used principally by the author for compression testing.

Figures 1, 2, and 3 show the apparatus which was used in these tests. Figure 1 is a schematic diagram showing the various parts and the manner in which they are assembled. Figure 2 is a photograph of the pressure equipment in place between the platens of the testing machine. Figure 3 is an over-all view of the test setup, including the testing machine, arranged for a compressive test.

A detailed description of the pressure equipment is presented in Appendix A.

## SPECIMENS AND SPECIMEN PREPARATION

All of the specimens which were used in these tests were taken from quarried rock pieces or cores which were readily available to the author during the test period. Complete geological descriptions are unavailable. However, thin sections of the various specimens were prepared and examined microscopically. Further examination was made of corresponding hand specimens. Resulting descriptions are given in Table I - XIII appearing in Appendix B. The tables also indicate whether the test specimens were taken from quarried or cored samples. In all instances in specimens taken from cored samples, the longitudinal axis of the specimen was taken parallel to the longitudinal axis of the cored sample. In specimens from quarried samples, orientations of the specimens were not known.

In most cases, the test specimens were obtained from the larger sample using a commercial diamond core drill, three-fourths inch outside diameter, one-half inch inside diameter, and with a four inch core barrel. After coring, the specimens were ground to one inch in length, and the ends squared and ground parallel. A smooth surface finish on the specimens was obtained with the core drill.

In other cases, especially the shales, it was impossible to obtain specimens with the core drill. Specimens for these samples were obtained by sawing the large sample



into square cross-section blocks of approximately the correct size and then grinding the surface to the desired diameter.

The major portion of the specimens were tested in the air-dry condition, that is, no particular effort was made to control accurately the moisture content of the specimens. The fluid used as the transmitting agent for the confining pressure was denied access to the specimen during the test by the plastic tube sheathing the specimen. The practice of jacketing the specimen followed that of Griggs<sup>4</sup>, who states that there is much evidence indicating that rocks at depth are not saturated with water. He observed that the strength of Solenhofen limestone under 10,000 atmospheres confining pressure increased 40 percent from the non-jacketed to the jacketed condition.

Names by which the various formations are designated may or may not be indicative of their true character. The designations are those which are in common use for the rock. More faith as regards the composition of the formations should be placed in the petrographic descriptions than in the name designations.

## TEST PROCEDURE

Figure 4 is a photograph of a specimen assembled as a unit with the upper piston, the end pieces, the brass sleeves, and the lower support. This assembly was placed in the test cavity and a sufficient amount of hydraulic oil was added to bring the level up to slightly below the "O" ring in the test cavity, being certain that the lower piston was pushed against the piston of the hydraulic jack. In tests at atmospheric pressure, no oil was used in the test cavity. The nut T was placed in position, and the extension arm to the dial indicator plunger was installed. The nut T was then partially tightened before the upper plate  $L_1$  was assembled. Generally, the upper plate was not fully clamped down in place until the nut T was screwed into its lowest position. Small grooves ground into the nut threads allowed entrapped air in the test cavity to escape. This procedure produced an initial hydrostatic pressure in the test cavity, the magnitude of which was dependent upon the exact amount of oil placed in the cavity. Additional confining pressure was obtained by operation of the hydraulic hand pump, thus forcing piston  $P_2$  further into the test cavity.

After centering the pressure apparatus on the platen of the testing machine, the platen was raised until the steel ball in the upper plate socket contacted the pressure plate on the crosshead of the machine. Jones<sup>9</sup>, in calibrating the equipment, found that the total weight

of the equipment parts supported by the upper piston is 32 pounds. It was also found that the average force required to overcome friction forces which the "O" ring packings exert on the pistons is 100 pounds. The friction force must be subtracted from and the weight of the parts on the upper piston must be added to the force indicated by the testing machine. The author placed a load on the apparatus slightly in excess of the difference between the friction force and that due to the weight of the parts, or 68 pounds. This was done to insure that the support R was properly seated, and that all components of the specimen assembly were in contact with each other. The dial indicator was set to zero at this point.

The rate of movement of the machine platen was adjusted by use of the calibrated valve on the machine control panel. The strain rate for these tests was approximately 1.5 percent per minute. Deflection readings were taken on the dial indicator at points corresponding to divisions on the dial, and readings were taken on the testing machine load indicator at corresponding points. During testing, the hydraulic hand pump was operated as needed to compensate for small losses in confining pressure occasioned by leakage past the "O" ring packings.

After fracture, or after reaching the point of maximum deflection as dictated by the available stroke of the upper piston, the load and the confining pressure were relieved. The specimen was carefully removed from the

cavity so as not to allow separation of the specimen assembly components. The jacket was cut away to reveal the deformed specimen.

Prior to testing, measurements on the specimen size were made and recorded. After testing, measurements of the specimen length, maximum diameter, and angles of failure were made where practical.

The method of measuring deformation was such that the total deformation of the specimen assembly, including that of the upper piston, the steel end pieces, and the lower support, was measured. Thus, in order to obtain the specimen deformation, it was necessary to determine the extraneous deformations. This was done by making tests using a steel specimen of the same size and shape as the rock specimens. Since the modulus of elasticity for the steel was known, deformations in the steel specimen under various conditions of stress were calculated and subtracted from the total measured deformations observed during the test. The difference was the apparatus deflection. A calibration curve was prepared in which apparatus deflection was plotted against differential stress on the specimen. This curve was used in determining the specimen deformation during tests on rock samples.

## RESULTS OF TESTS

Stress-strain curves were prepared for all of the specimens tested. In those cases where all tests at a given confining pressure were consistent, an average curve is presented for the particular condition. In other cases, single tests deviated somewhat from the average determined from a group of other tests made under the same conditions. Since enough tests at any given condition were not run to establish reliable confidence limits, the deviating curve was also plotted. The stress-strain curves are presented in Appendix B.

Although the curves are referred to in the familiar "stress-strain" designation, it will be noted that the ordinate of the curve is actually differential stress. The total axial stress on the specimen is the differential stress plus the confining pressure. Determination of the differential stress in the rock specimens was based upon the assumptions that the volume of the specimen remained constant during the deformation process and that lateral deformation was constant along the length of the specimen. The latter assumption is in error in those cases where specimens exhibit a ductile type behavior and assume a barrel-like shape. However, this method of determining the differential stress is more accurate than use of the conventional method based upon the original cross-sectional area of the specimen. Handin<sup>8</sup> also based his differential stress calculations upon the two assumptions listed.

The derivation of the differential stress formula follows:

Assuming constant volume during deformation,

$$V = A_o L_o = AL \quad (1)$$

where  $V$  = specimen volume,

$A_o$  = original cross-sectional area,

$L_o$  = original length,

$A$  = deformed cross-sectional area,

and  $L$  = deformed length.

From equation (1)

$$A = \frac{A_o L_o}{L} \quad (2)$$

The differential stress  $\sigma$  in the specimen at any time is

$$\sigma = P/A \quad (3)$$

where  $P$  = differential load applied to the ends of the specimen.

Substituting equation (2) in equation (3) gives

$$\sigma = PL/A_o L_o \quad (4)$$

$P/A_o$  is the differential stress applied to the specimen based upon the original cross-sectional area, and  $L/L_o$  is equal to  $(1-\epsilon)$ , where  $\epsilon$  is the unit deformation, or strain.

Therefore, from equation (4)

$$\sigma = \sigma_0 (1 - \epsilon) \quad (5)$$

where  $\sigma_0$  = stress based upon the  
original cross-sectional  
area.

Photographs showing typical deformed and fractured rock specimens for various conditions were also prepared. Captions for the photographs indicate the confining pressure, the maximum differential stress applied to the specimen, and the unit deformation at fracture or termination of the test. The photographs and stress-strain curves are presented in Figures 5 through 32 in Appendix B.

Descriptions of the fractures obtained for each specimen tested are included in Tables I-VIII, together with the petrographic descriptions of the formations. In those cases where the specimen did not remain intact, the angles which planes of fracture made with the compression axis of the specimen were measured. These measurements are probably somewhat inaccurate, especially in those cases where the specimen failed predominantly in longitudinal splitting with only very small shear surfaces at the ends of the longitudinal splits.

In those cases where the specimen remained intact, it was assumed that eventual failure would have occurred along planes outlined on the specimen surface by a network of lines. Griggs states that these lines, which he takes to be surface expressions of internal shear surfaces, are analogous to Luders lines in metals. Angles of planes indicated by the surface lines were measured with respect to the compression axis of the specimen and are presented in the tables.



## DISCUSSION AND ANALYSIS OF RESULTS

In discussing the results obtained on these tests the same terms defined by Handin<sup>8</sup> will be used. "Flow" will signify any deformation not instantly recoverable, except fracture. "Fracture" will signify deformation with loss of cohesion. "Yield strength" and "ultimate strength" will imply the conventional meaning of these terms under specified environmental conditions. "Strength" used singly will signify the differential stress at fracture for those specimens which exhibited no flow, and ultimate strength for those specimens which did flow.

Generally, all specimens exhibited a marked increase in compressive strength with increasing confining pressures. One group of saturated sandy shale specimens tested under conditions allowing exposure of the specimen to the confining liquid was an exception.

Failures at atmospheric pressure were generally of the tension type, having wedges associated with the longitudinal splitting. The shear wedges were generally formed near the ends of the specimens. Griggs<sup>4</sup> had also observed this type of failure. He assumes that the shear wedges provide sufficient lateral force perpendicular to the compression axis of the specimen so as to exceed the tensional strength of the material, causing splitting. The angles formed by the wedges at the ends of the specimens varied considerably with different materials, but were reasonably consistent for a given material. The

maximum wedge angle measured was  $36^\circ$ , considerably under the theoretical maximum shear stress plane at  $45^\circ$ .

In some cases, the fracture face was composed of failures at two angles, the larger of the two occurring near the ends of the specimen. This usually occurred when the specimens were tested under confining pressures. The portion of the fracture face associated with the smallest angle generally was the major portion, and is designated hereafter as the major failure plane. The major failure plane generally was more nearly parallel to the compression axis of the specimen than was the smaller plane located near the end of the specimen. Also, at larger confining pressures, the major failure angles generally increased. These observations are consistent with those of Griggs<sup>4</sup> who concluded that tension failures are inhibited by confining pressure. Thus, the fracture planes, which he observed to be an integration of minute tensile and shear type failures, progressively change from the predominant tensile type failure to failures consisting of more and more shear as confining pressure increases.

On those specimens which exhibited a ductile type behavior, a network of lines was generally visible on the surface. Angles which these lines made with the compression axis were measured where possible. In one instance (shale from Duval County, Texas) a specimen

was broken after it had assumed a barrel shape during testing. The surface lines were measured at  $38^\circ$ , but the fracture plane was at  $32^\circ$ . Thus, it is not certain that the surface lines are indications of planes upon which fracture would occur if deformation were continued.

### ANHYDRITE

This formation is one which exhibits a transition from brittle to ductile type behavior at an early stage as the confining pressure increases. The apparent transition is in the confining pressure range from zero to 2500 psi. The major failure planes at atmospheric pressure occurred at angles of  $16^\circ$ - $18^\circ$  from the compression axis. There was some clear evidence of tension failure combining with a shear failure on one specimen. On another, a plane having a larger angle than the major fracture intersected the major failure plane near the end of the specimen.

As confining pressure increased, the angle of the lines on the barrel shape specimens increased from  $32^\circ$  to  $36^\circ$ .

With increasing confining pressure, differential stress required to produce flow increased to a maximum of 28,000 psi. at 10,000 psi. confining pressure. Thus, the increase in strength from atmospheric pressure to 10,000 psi. confining pressure was approximately 460%, using

approximate yield strength as the strength criterion in those cases where flow occurs.

#### KNIPPA BASALT

Knippa basalt exhibited a brittle type behavior through confining pressures including 15,000 psi. Its increase in strength from its strength at atmospheric pressure was 83% at 10,000 psi. confining pressure, and 147% at 15,000 psi. confining pressure. Failures at atmospheric pressure were predominantly of the tension type. Wedge angles were approximately 22°. At 10,000 psi. confining pressure, the major failure angles varied from 26° to 31°. In two cases angles of 36° and 45° were observed near the ends of the specimens.

#### RUSH SPRINGS SANDSTONE

At atmospheric pressure, these specimens failed with brittleness, exhibiting tensile type failures with wedge angles of approximately 18°-21°. At higher confining pressures, the specimens were still brittle, but broke into fewer pieces (generally two or three major ones) than at atmospheric pressure. Major failure angles varied from 21° to 35°. In one instance, a failure angle of 41° was observed near the end of the specimen.

The strength of this formation increased with confining pressure from 26,000 psi. at atmospheric pressure to 90,000 psi. at 15,000 psi. confining pressure, an increase of 346%.

### CHICO LIMESTONE (COARSE-GRAINED)

Only three specimens of this formation were tested. At atmospheric pressure, the fracture was predominantly tensile. Surfaces other than the tensile fracture were white and powder-like, indicating relative motion between adjacent pieces. At 2500 psi. confining pressure the specimens broke into two major pieces, with essentially all of the fracture surface being white and powder-like. The increase in strength from atmospheric to 2500 psi. confining pressure was 131%.

### AUSTIN CHALK

These specimens, being very soft, fractured at low stresses at atmospheric pressure. Results were inconsistent as shown by the stress-strain curves in Figure 14. One specimen appeared to flow at a stress of only 500 psi., but examination showed that this specimen had failed predominantly in tension. Another one of the specimens tested at atmospheric pressure failed at a 15° angle, with an angle at the end of 29°.

At 10,000 psi. confining pressure, all of the specimens broke with what appeared to be a progressive crumbling type failure at some area of the specimen, generally near the center. The specimens apparently assumed a barrel-like shape prior to fracture.

This material has no apparent yield point, but begins to flow immediately upon application of a differential

stress. It was not possible to ascertain the point at which failure occurred at the higher confining pressures. Therefore, the usual criterion of increase in strength based upon stress at fracture or yield is not applicable for this formation.

#### D-1 FORMATION

There appear to be a number of inconsistencies in results obtained on this formation. The curve at 5000 psi. confining pressure deviates from the range of the elastic portion of the stress-strain curves established by all of the other tests. One of the specimens tested at 10,000 psi. confining pressure was deformed 17%. This specimen assumed a barrel-like shape before fracture. Another specimen at 10,000 psi. confining pressure fractured on one end and did not assume a barrel shape. Another apparent inconsistency is in the results of the test at 7500 psi. confining pressure, which show an ultimate strength exceeding that achieved at 10,000 psi.

The strength increase of this formation at 15,000 psi. over that at atmospheric pressure was 263%.

#### WHITE DOLOMITE

At atmospheric pressure, the failures were predominantly longitudinal. A number of small surfaces at angles varying from  $23^{\circ}$  to  $32^{\circ}$  were visible on the fracture faces, appearing white and powder-like. At

10,000 psi. confining pressure, the specimens broke into two pieces, the failure surfaces also appearing white and powder-like. Major failure angles varied from  $18^{\circ}$  to  $32^{\circ}$ , with the maximum angles at the ends of the fractures varying from  $28^{\circ}$  to  $38^{\circ}$ . At 15,000 psi., the specimen broke in a brittle manner as in the 10,000 psi. tests, with the failure angle at  $34^{\circ}$ . The stress-strain curve indicates that the specimen was able to support some load after the ultimate strength was reached. At 15,000 psi., the strength of white dolomite was approximately 300% higher than at atmospheric pressure.

#### VIRGINIA LIMESTONE

All of the specimens in this group broke in a brittle fashion. The stress-strain curve for one test at 10,000 psi. indicates that this specimen flowed before fracture. However, subsequent examination of the specimen did not indicate this to be the case.

Of all formations tested, Virginia limestone exhibited the greatest strength at atmospheric pressure and at confining pressures of 10,000 psi and 15,000 psi. This may be partly explained by the fact that the material is composed almost entirely of dolomitic carbonate grains, with no binder. Tests at atmospheric pressure and at 10,000 psi. confining pressure were on specimens from two different samples. At atmospheric pressure the difference in results was sufficiently large to warrant the plotting

of results for each. At 10,000 psi. confining pressure, results were closer together, and only one curve for the two samples was plotted, with the exception of one instance where the specimen appeared to flow. Based upon the highest compressive strength at atmospheric pressure, the strength increased 163% at 15,000 psi. confining pressure.

Failures at atmospheric pressure were predominantly of the tension variety, with wedge angles varying from  $23^{\circ}$  to  $35^{\circ}$ . At 10,000 psi., failures were consistent along planes of  $16^{\circ}$ - $18^{\circ}$ , with the specimen breaking into two major pieces. Maximum angles near the ends of the fractures varied from  $28^{\circ}$  to  $41^{\circ}$ . At 15,000 psi. pressure, the failure angle between the two major pieces was  $21^{\circ}$ , with the maximum angle being  $23\text{-}1/2^{\circ}$  at the end of the fracture.

#### FINE-GRAINED CHICO LIMESTONE

Specimens from two different samples of this material were tested. The two samples displayed remarkably different characteristics. In classifying the material by petrographic analysis, only a deformed specimen was available for the second core. This specimen was described as being very similar to the coarse-grained Chico limestone. In fact, the stress-strain curve for this sample at atmospheric pressure was also very similar to that for coarse-grained Chico limestone.



Specimens from Core No. 1 exhibited brittle properties at atmospheric and 10,000 psi. confining pressure. At atmospheric pressure, some longitudinal splitting was observed, with a wedge angle of  $24\text{-}1/2^\circ$ . At 10,000 psi. pressure, the specimens broke into two pieces at angles of  $24\text{-}1/2^\circ$  and  $29\text{-}1/2^\circ$ . Increase in strength was 140% at 10,000 psi. pressure.

Specimens from Core No. 2 behaved quite differently. At atmospheric pressure, the compressive strength of Core No. 1 was 136% higher than Core No. 2. At the higher confining pressures, Core No. 2 flowed. It may be noted that at 10,000 psi. pressure, a differential stress of 60,000 psi. was required to fracture the higher strength material, whereas for the lower strength material, a differential stress of only 38,000 psi. was required to produce flow. Strains up to 27% were achieved without loss of cohesion on a specimen from Core No. 2.

Failures of Core No. 2 specimens were characteristically longitudinal at atmospheric pressure, with wedge angles from  $28^\circ$  to  $31^\circ$ . At 7,500 psi. and 10,000 psi. confining pressures, resultant lines on the surface of the barrel-shape specimens were at angles of  $31^\circ$  to  $34^\circ$ . Increase in strength at 10,000 psi. pressure was 245% over that at atmospheric pressure.

#### CARTHAGE MARBLE

Two different samples of this material were also tested. Sufficient variation between results on the

samples was noted so that results for each were plotted in the stress-strain curves. Both samples exhibited ductile behavior at higher confining pressures. At atmospheric pressure, the specimens broke with some longitudinal splitting evident. Angles varied from  $18^{\circ}$  to  $30^{\circ}$ . At higher confining pressures, specimens from both samples displayed ductile properties, with the apparently predominant angle of surface lines being  $36^{\circ}$ . Lines on one specimen were at  $26^{\circ}$ .

Increase in strength from atmospheric pressure to 10,000 psi. confining pressure was 260% for Core No. 1 and 350% for Core No. 2.

#### WYOMING RED BED

Tests at atmospheric pressure on this material were inconsistent as shown by the stress-strain curves in Figure 26. At atmospheric pressure and at 10,000 psi. pressure the specimens exhibited brittle fractures. At 15,000 psi. pressure, however, the specimen appears to have been at the borderline between brittle and ductile behavior. Though the stress-strain curve indicates flow in the material and the specimen assumed a barrel-like shape, fracture did occur.

Failure angles at atmospheric pressure varied from  $16^{\circ}$  to  $26^{\circ}$ . At 10,000 psi. pressure, specimens broke into two or three major pieces at angles from  $21^{\circ}$  to  $33^{\circ}$ . At 15,000 psi. pressure, the failure angle was  $35^{\circ}$ .

Increase in strength from the average strength at atmospheric pressure was approximately 88% at 10,000 psi. and 15,000 psi. confining pressures.

#### SHALE

At atmospheric pressure, shale specimens broke into many pieces, mostly longitudinal. Wedge angles were at 15° to 23°. At 10,000 psi. pressure, specimens broke into two pieces at angles of 30° and 38° across the distinct bedding planes of the material. Between 10,000 psi. and 15,000 psi. pressure, a transition between brittle and ductile type behavior occurred. At 15,000 psi., the specimen assumed a barrel-like shape with surface lines at angles of 38°. After testing, however, the specimen fractured very easily on a plane at 32°.

The strength increase of this formation at 15,000 psi. confining pressure over that at atmospheric pressure was approximately 200%.

#### SANDY SHALE

This formation was tested under four different sets of conditions in an attempt to determine the effect of saturation by water upon jacketed and non-jacketed specimens. Specimens which were saturated with water prior to testing gained about 4% by weight during saturation.

Results of tests on specimens which were dry prior to testing and jacketed during the tests are given in

Figure 31. At atmospheric pressure the failures were brittle, but at 5,000 psi. and 10,000 psi. confining pressure, all specimens exhibited ductile type behavior. Stress-strain curves, shown in Figure 32, were quite similar on specimens which were saturated prior to testing and jacketed during the test. Failures were vastly different, however. Whereas the dry specimens assumed a barrel shape at 10,000 psi. pressure, and remained in one piece, the saturated specimens appear to have barrelled somewhat, but fractured before the tests were discontinued. Appearance of the fractures were very unusual. The specimens broke into five or six disks of approximately equal thicknesses on planes perpendicular to the axis of compression.

Specimens which were exposed to the confining liquid during testing all exhibited brittle type behavior. Those saturated prior to testing showed no increase in strength with increasing pressure. In fact, the average strength of all specimens tested in this saturated group at various pressures was slightly below that of a dry jacketed specimen tested at atmospheric pressure. All broke into two pieces at major failure angles of  $21^{\circ}$  to  $26^{\circ}$ . Two specimens which were dry prior to testing at 5000 psi. and 10,000 psi. confining pressures broke into two major pieces at angles of  $38^{\circ}$  and  $48^{\circ}$ , respectively. An apparent inconsistency in these tests was that the specimen at 5000 psi. showed a

greater strength than at 10,000 psi. confining pressure.

Which of these four conditions most closely approximates the actual condition at the bottom of an oil well bore hole is problematical. If the formation is free of water, then either the case of a dry specimen with a jacket or a dry non-jacketed specimen would mostly closely approximate the actual condition. Of these two possibilities, susceptibility of the formation to penetration of a fluid would determine which is more probable. If a homogeneous, compact formation with low permeability is being drilled, then the case of the dry jacketed specimen would probably be most applicable of the four cases considered.

Increase in strength of the dry jacketed specimen over that at atmospheric pressure was 175% at 5000 psi. confining pressure and 275% at 10,000 psi. confining pressure.

#### CORRELATION WITH DRILLING TESTS

Mr. R. A. Cunningham<sup>3</sup> has conducted drilling tests upon rock formations under pressure using a one and one-quarter inch two-cone bit. Pressures used were in the same range as those used by the author. Curves for various formations were prepared in which drilling rate was plotted against confining pressure.

Based upon a paper by Kuhne<sup>10</sup>, Cunningham derived an expression whereby drilling rate of a material may be predicted if certain of its physical properties are known.

If the principal stresses acting on a material in two orthogonal directions are known, such as the differential stress on the end of a rock cylinder and the confining pressure surrounding the cylinder, then the shear stress on any plane in the material may be determined by use of a Mohr's circle construction, assuming a two-dimensional state of stress. In this type of graphical construction, points on the abscissa represent normal stresses, and those on the ordinate represent shear stresses. Thus, in tests such as those conducted by the author, a Mohr's circle may be drawn for each specimen tested, where the diameter on the normal stress coordinate axis is determined by the maximum differential stress applied to the ends of the specimen. As observed in the results of the tests, for each value of confining pressure, there exists a corresponding value of ultimate strength for a given material. All Mohr's stress circles thus determined may be enveloped by a common boundary curve. A normal to the bounding curve at the point at which it touches the stress circle makes an angle  $2\alpha$  with the normal stress axis. The angle  $\alpha$  represents the inclination of the fracture plane to the compression axis.

The expression derived by Cunningham is:

$$K\bar{V} = \frac{(\sigma_{ro})^3}{\left[ \sigma_{ro} + p \left( \frac{1+\cos 2\alpha}{1-\cos 2\alpha} - 1 \right) \right]^3}$$

where  $\bar{K}$  = proportionality constant, in hrs./ft.

$V$  = drilling rate in ft./hr.

$\sigma_{ro}$  = ultimate compressive strength at  
atmospheric pressure in lb./in.<sup>2</sup>.

$p$  = confining pressure in lb./in.<sup>2</sup>.

and  $\alpha$  = angle of inclination of the fracture  
plane with the compression axis.

The angles  $\alpha$  were determined for Wyoming red bed and shale by approximating the Mohr's circle boundary curve with a straight line. For these two formations, this approximation is justified. Use of the angles  $\alpha$  thus determined were used in the expression together with other data secured experimentally, and values for  $K\bar{V}$  determined at various pressures. Results are plotted in Figures 33 and 34, together with experimental results obtained from the drilling tests. Correlation for these two formations appear to be good.

## CONCLUSIONS

1. All formations tested in the dry, jacketed condition exhibited increases in compressive strength with increasing confining pressure. Quantitative results were obtained for this increase for all formations tested except Austin chalk, a material which displayed no unique yield or ultimate strength in tests in which the confining pressure was greater than atmospheric.
2. All formations tested in the dry, jacketed condition exhibited brittle behaviors at atmospheric pressure. Those exhibiting a transition from brittle type to ductile type behavior in the confining pressure range 0 to 15,000 psi. were anhydrite, D-1 formation, fine-grained (?) Chico limestone, Carthage marble, shale, and sandy shale. Wyoming red bed appeared to be at the borderline between brittle and ductile behavior at 15,000 psi.
3. Results of strength tests on Wyoming red bed and shale were used in an expression predicting drilling rate at various pressures. Correlation of these predictions and results of drilling tests under pressure appear to be good for these two formations.



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## APPENDIX A

### DESCRIPTION OF PRESSURE EQUIPMENT

The pressure testing equipment was designed to accommodate a test specimen one-half inch in diameter and one inch long up to confining pressures of 21,000 psi. Referring to Figure 1, the specimen S is located in a cavity in the pressure vessel V. A light hydraulic oil is used as a pressure transmitting agent surrounding the specimen. Immediately above and below the specimen, replaceable soft steel slugs are used to protect the ends of the hardened pieces, piston  $P_1$  and support R. They also serve as transition pieces between the relatively soft specimen and the hardened piston and support so that smaller discontinuities of lateral deformation at the end of the specimen result. Soft brass sleeves, which may be seen in Figure 4, are used to assist in aligning the upper piston, slugs, specimen, and support R. These replaceable sleeves, two of which are used with each assembly, are approximately .010 inch thick,  $1/2$  inch long, and have a cylindrical portion and a conical portion. The conical portion fits over the tapered ends of the load pieces  $P_1$  and R, while the cylindrical portion fits over the slugs and approximately  $1/8$  inch of the specimen. The end of the cylindrical portion is slotted about  $1/8$  inch from the end at eight places equally spaced around the circumference, so that little restraint to lateral deformation of

the specimen is provided other than the shear restraint on the face of the specimen. A piece of plastic tubing is fitted over the entire specimen assembly, the length being sufficient to extend from about 1/8 inch on the cylindrical portion of piston  $P_1$  to the cylindrical portion of the support R. In addition to protecting the specimen from contact with the confining liquid, use of the tubing provides an easy means for assembly and disassembly. If tests are desired in which the fluid has access to the specimen, several holes are cut in the tubing portion immediately surrounding the specimen.

Pistons  $P_1$  and  $P_2$  are the same diameter. They are yoked together by means of three equally spaced tie rods Y which are connected to the upper plate  $L_1$  and the intermediate plate  $L_3$ . Piston  $P_2$  is supported by a small commercial hydraulic jack J, which provides a movement of 5/8 inch. The jack is connected to a hydraulic hand pump, shown in Figure 3. Operation of the hand pump forces piston  $P_2$  into the cavity, thus increasing the hydrostatic pressure around the specimen. Maximum confining pressure available with this equipment is 21,000 psi. The stop R is drilled so that the confining liquid has free access to both pistons. When the desired confining pressure is obtained by operation of the hand pump, as indicated by the pressure gage, a valve on the pump is closed so that pistons  $P_1$  and  $P_2$  remain a constant distance apart,

irregardless of the load applied to the specimen. Thus, the pressure in the cavity remains essentially constant during the test.

The upper piston  $P_1$  enters the cavity through the threaded plug T. The plug T, which provides access to the test cavity, has a closely ground bore and a recess for an Neoprene "O" ring seal. The lower external cylindrical portion of the plug is also ground to assist in providing a seal between the plug and the pressure vessel.

The pressure vessel is supported by three equally spaced columns C. During compression tests, an auxiliary ring support, shown in Figure 2, is used between the lower ends of the three columns and the platen of the testing machine. A plate  $L_2$  provides lateral support for the columns. A similar plate  $L_1$  at the top of the apparatus is provided with a ball socket in the threaded projection. A hardened steel ball is used between plate  $L_1$  and the cross head of the test machine in order to eliminate accidental eccentric loading of the apparatus.

A bar, which is equipped with a slotted hole and screw clamp on one end, is attached to the upper end of piston  $P_1$ . The opposite end of the bar contacts the plunger of a dial indicator D mounted on the side of the pressure vessel. This arrangement is used for obtaining deformation measurements. The axial deformation measured is that of the entire specimen assembly and must be

corrected to specimen deformation by subtraction of the extraneous deformations.

Differential compressive force is applied to the specimen by advancing piston  $P_1$  into the test cavity. The force thus applied is transmitted through the specimen to the lower platen of the testing machine.

A Baldwin testing machine, shown in Figure 3, was used in these tests. The lower platen of the hydraulic loading unit moves upward while the cross head remains fixed in compression testing. Rate of application of load is maintained precisely by manipulation of a calibrated hydraulic valve located on the control panel. The load applied to the test apparatus is transmitted by a hydraulic capsule to the weighing mechanism in the control unit, and is read directly on the load indicator. Three load ranges are available: 0-12,000 pounds, 0-60,000 pounds, and 0-300,000 pounds. Generally, the smallest range possible consistent with the strength of the specimen is used in order to obtain the greatest accuracy in load measurements.

## APPENDIX B

### LIST OF FIGURES AND TABLES IN ORDER

- Figure 1. Schematic Diagram of the High Pressure Strength Test Apparatus (After Jones, 1954).
- Figure 2. Apparatus for Conducting Strength Tests on Rock Under Hydrostatic Pressure (After Jones, 1954).
- Figure 3. Strength Test Apparatus in Place in Baldwin Testing Machine. Equipment is Arranged for Compressive Tests (After Jones, 1954).
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Figure 33. Comparison of Laboratory Results with Results From Theoretical Equations for Wyoming Red Bed (After Cunningham, 1955).

Figure 34. Comparison of Laboratory Results with Results From Theoretical Equations for Shale (After Cunningham, 1955).

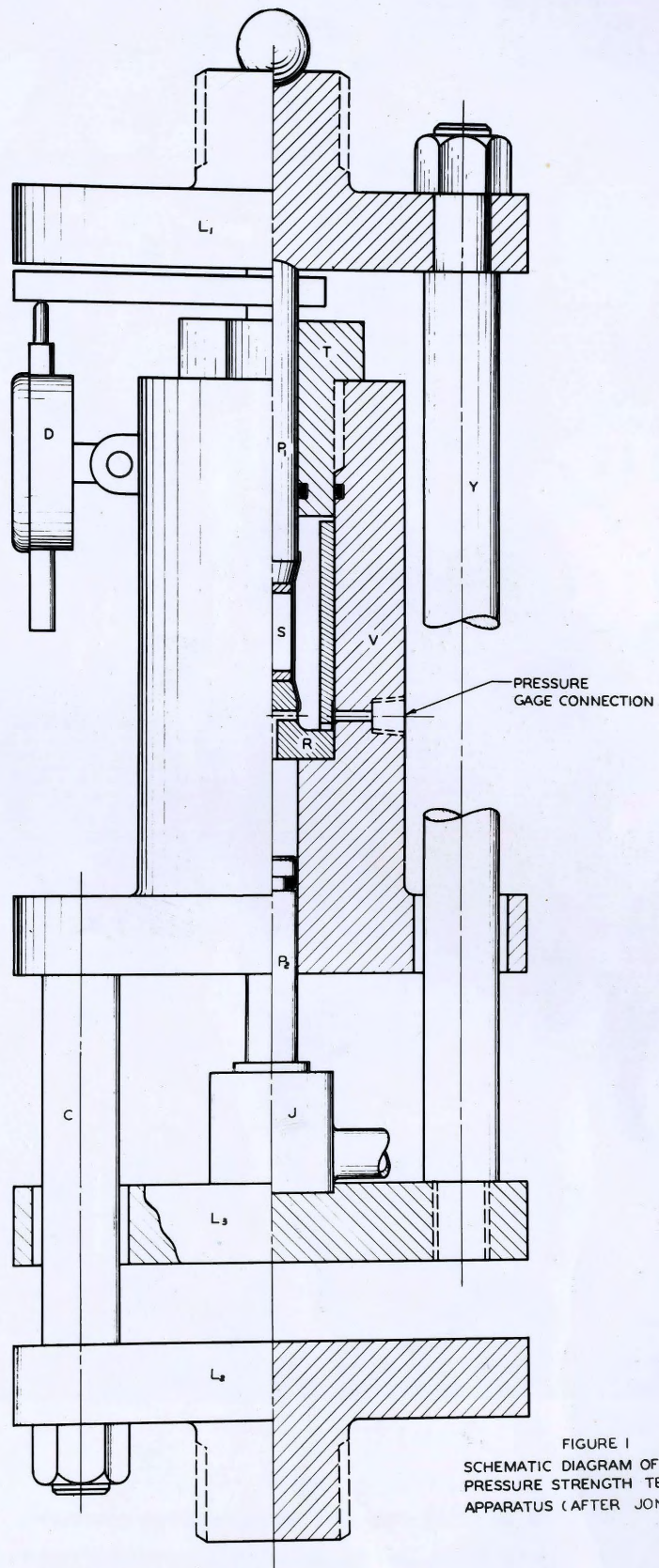


FIGURE I  
SCHEMATIC DIAGRAM OF THE HIGH  
PRESSURE STRENGTH TEST  
APPARATUS (AFTER JONES, 1954)



FIGURE 2

APPARATUS FOR CONDUCTING STRENGTH TESTS ON ROCK  
UNDER HYDROSTATIC PRESSURE. (AFTER JONES, 1954)





FIGURE 3  
STRENGTH TEST APPARATUS IN PLACE IN BALDWIN  
TENSILE TESTING MACHINE. EQUIPMENT IS ARRANGED  
FOR COMPRESSIVE TESTS. (AFTER JONES, 1954)



FIGURE 4  
SPECIMEN ASSEMBLY SHOWING THE UPPER PISTON,  
BRASS SLEEVES, SUPPORT, AND PLASTIC JACKET.

TABLE 1. ANHYDRITE-PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS

SOURCE OF SPECIMENS: Specimens were taken from cores  
from Leduc Field, Elberta, Canada.

PETROGRAPHIC DESCRIPTION:

Rectangular anhydrite grains ranging from 0.1 to 2 millimeters long make up approximately two-thirds of the sample. Cutting the anhydrite and filling the interstices between the anhydrite grains is fine grained, fibrous, gypsum which comprises another one-third of the rock but varies markedly in quantity from place to place. One percent of the rock consists of irregular grains of carbonate. The sample is massive.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen. In cases of specimens remaining intact after testing, angles are those made by slip planes indicated by surface lines measured with respect to the compression axis.

Reference: Figures 5 and 6.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
68	0	Some longitudinal splitting. Angle = 16°-18° approximately.
69	0	Two major pieces. Angle = 18° approx. Max. angle at end of specimen = 34°.
136	2500	Specimen in barrel shape. Wedges formed at each end. Angle = 32°.
82	5000	Specimen in barrel shape. Angle = 32°.
81	7500	Specimen in barrel shape. Disc broken off on one end. Angle = 36°.
74	10000	Specimen in barrel shape. Angle = 36°.
75	10000	Specimen in barrel shape. Angle = 36°.





SPECIMEN NO. 69  
CONF. PRESS. = 0 PSI  
MAX. DIFF. STRESS = 8000 PSI  
STRAIN = 0.5%



SPECIMAN NO. 136  
CONF. PRESS. = 2500 PSI  
MAX. DIFF. STRESS = 16000 PSI  
STRAIN = 20.0%



SPECIMEN NO. 82  
CONF. PRESS. = 5000 PSI  
MAX. DIFF. STRESS = 21500 PSI  
STRAIN = 24.0%



SPECIMEN NO. 81  
CONF. PRESS. = 7500 PSI  
MAX. DIFF. STRESS = 27000  
STRAIN = 24.5%



SPECIMEN NO. 75  
CONF. PRESS. = 10000 PSI  
MAX. DIFF. STRESS = 30000 PSI  
STRAIN = 21.0%

FIGURE 5

ANHYDRITE SPECIMENS AFTER COMPRESSION  
AT VARIOUS CONFINING PRESSURES



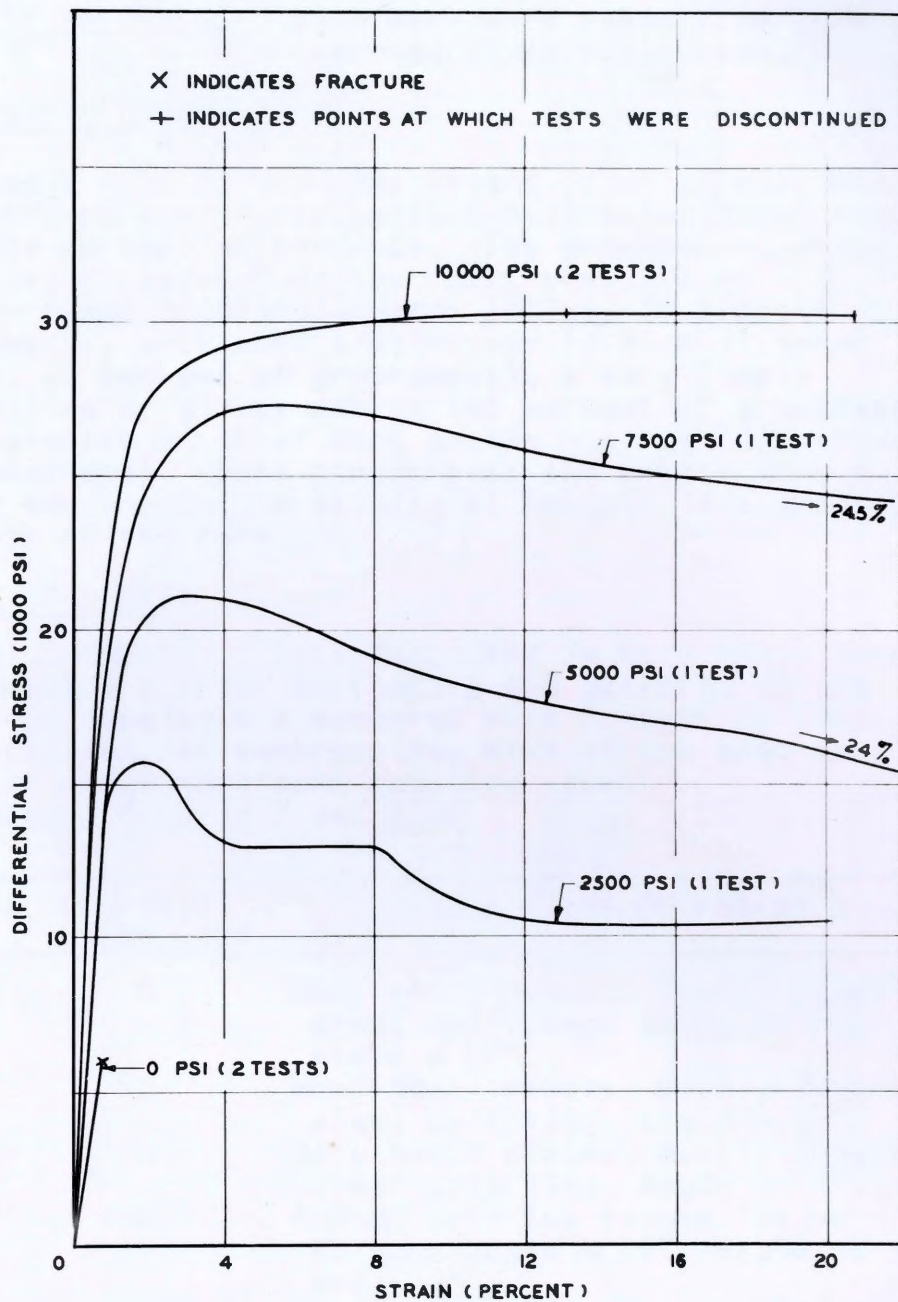


FIGURE 6  
STRESS-STRAIN CURVES OF ANHYDRITE TESTED IN  
COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE II. KNIPPA BASALT - PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from rock  
quarried at Knippa, Texas.

PETROGRAPHIC DESCRIPTION:

The sample is a porphyritic basalt in which phenocrysts of enstatite and pigeonite (0.5-millimeter long) comprise about 30 percent of the rock. The groundmass, which comprises 70 percent of the rock, consists of clinopyroxene (0.02-millimeter grains, 20 percent of groundmass), untwinned plagioclase (0.02-millimeter grains, 20 percent of groundmass), a very finely crystalline or glassy matrix (45 percent of groundmass), and magnetite or other dark opaque mineral (15 percent of groundmass). Both phenocrysts and matrix show a poorly developed flow banding at roughly 30 degrees to the axis of the core.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen.

None of these specimens remained intact.

Reference: Figures 7 and 11.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
45	0	Many small pieces. Mostly longitudinal splitting. Angle on one piece = 22°.
58	0	Many small pieces. Mostly longitudinal splitting. Angle = 22°.
103	0	Many small pieces. Mostly longitudinal splitting. Angle = 21°.
59	10000	Broken into two pieces. Major failure angle = 28°. Angle at end = 45°.
60	10000	Broken into two pieces. Major failure angle = 31°. Angle at end = 36°.
104	10000	Broken into two pieces. Fractured thru one end face. Angle = 30°.
105	10000	Broken into two major pieces. Angle = 26°.
106	15000	Broken into two pieces. Angle = 21°.



SPECIMEN NO. 103

CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 37500 PSI  
 STRAIN = 1.0%



SPECIMEN NO. 59

CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 64000 PSI  
 STRAIN = 1.1%



SPECIMEN NO. 106

CONF. PRESS. = 15000 PSI  
 MAX. DIFF. STRESS = 94000 PSI  
 STRAIN = 1.7%

FIGURE 7  
 KNIPPA BASALT SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES





SPECIMEN NO. 86  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 20000 PSI  
 STRAIN = 0.7 %



SPECIMEN NO. 50  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 82000 PSI  
 STRAIN = 1.8 %



SPECIMEN NO. 89  
 CONF. PRESS. = 15000 PSI  
 MAX. DIFF. STRESS = 90000 PSI  
 STRAIN = 1.8 %

FIGURE 8  
 RUSH SPRINGS SANDSTONE SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE IV. COARSE-GRAINED CHICO LIMESTONE -  
PETROGRAPHIC DESCRIPTION AND RESULTS  
OF TESTS.

---

SOURCE OF SPECIMENS: Specimens were taken from rock  
quarried at Chico, Texas.

PETROGRAPHIC DESCRIPTION:

About one-third of the rock consists of an unsorted mass of fine to coarse (2-millimeter) angular grains of calcite, fine grained limestone, foraminifera, and other shell fragments. These clasts are imbedded in a matrix of very fine grained limestone which comprises the remainder of the rock. The rock is massive.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen. None of these specimens remained intact.  
Reference: Figures 9 and 12.

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SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
125	0	Mostly longitudinal splitting, with split surfaces being granular. Shear (?) surfaces are powdery and white. Angle = $34^{\circ}$ .
126	2500	Broken into two major pieces. Practically all of fracture surface is powdery and white. One angle = $28^{\circ}$ , another angle = $30^{\circ}$ .
128	2500	Broken into two major pieces. Practically all of fracture surface is powdery and white. One angle = $32^{\circ}$ , another angle = $26^{\circ}$ .

---



SPECIMEN NO. 125  
CONF. PRESS. = 0 PSI  
MAX. DIFF. STRESS = 11500 PSI  
STRAIN = 0.7%



SPECIMEN NO. 128  
CONF. PRESS. = 2500 PSI  
MAX. DIFF. STRESS = 28500 PSI  
STRAIN = 0.9%

FIGURE 9  
COARSE CHICO LIMESTONE SPECIMENS AFTER  
COMPRESSION AT VARIOUS CONFINING PRESSURES



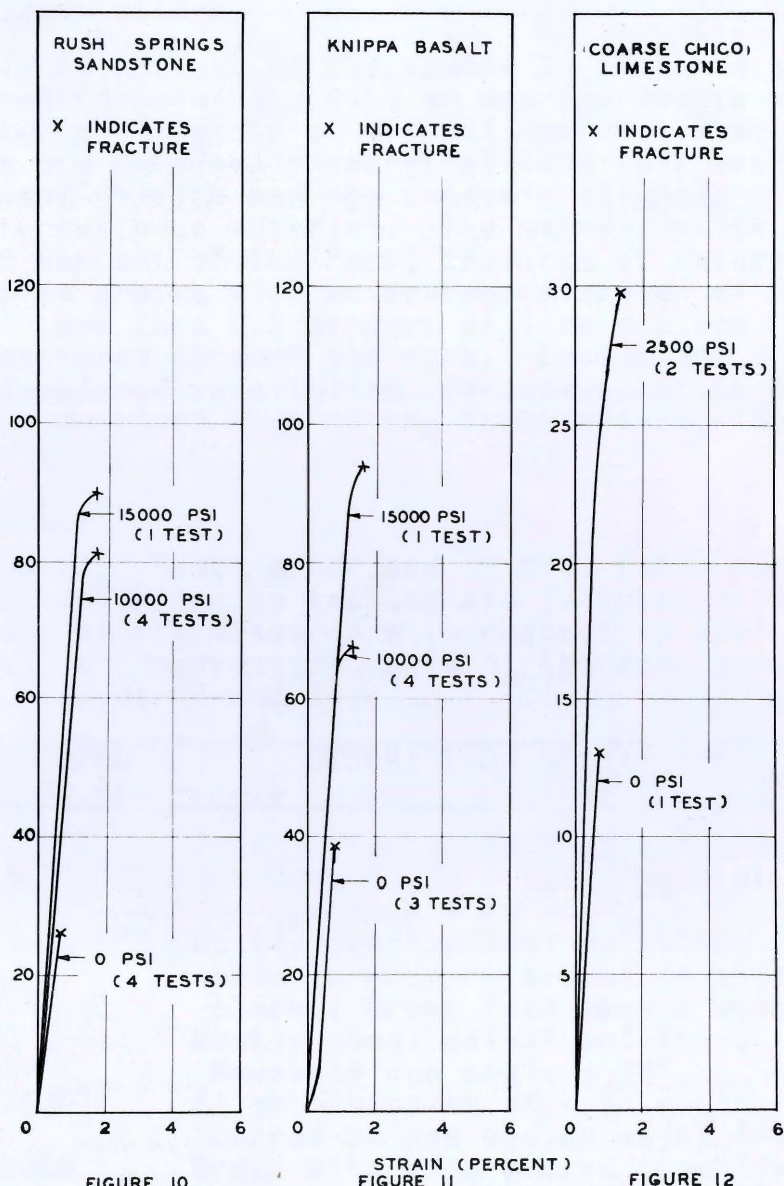


FIGURE 10  
FIGURE 11  
FIGURE 12

STRESS-STRAIN CURVES OF ROCK SAMPLES TESTED  
IN COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE V. AUSTIN CHALK - PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from rock quarried near Austin, Texas.

PETROGRAPHIC DESCRIPTION:

Approximately 60 percent of the sample is composed of recrystallized foraminifera with an average length of 0.2 millimeter and a width of 0.1 millimeter. The foraminifera are completely recrystallized to a mass of fine grained calcite and are commonly slightly stained by ferruginous material. The matrix, which comprises 40 percent of the rock, consists of interlocking calcite grains with an average diameter of 0.1 millimeter. Less than 0.5 percent of fine grained silica is scattered through the rock. Except for a moderately developed parallelism (Perpendicular to the length of the core) of some of the foraminifera, the rock is massive.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen.  
Reference: Figures 13 and 14.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
70	0	Broke into two major pieces. Major failure angle = 15°. Angle at end of specimen = 29°.
71	0	Mostly longitudinal splitting. Unable to measure angles on ends of pieces. Broke into many pieces.
129	0	Mostly longitudinal splitting. Measured one angle = 36°.
77	7500	Slight chipping of specimen occurred on one end. No major failure.
76	10000	Broke with progressive crumbling type failure near both end. Center portion assumed slightly barreled shape.
131	10000	Broke with progressive crumbling type failure near center of specimen. Appears to have assumed barrel shape before failure.
132	10000	Broke with progressive crumbling type failure near center. Appears to have assumed barrel shape prior to failure.





SPECIMEN NO. 71  
CONF. PRESS. = 0 PSI  
MAX. DIFF. STRESS = 500 PSI  
STRAIN = 5.5 %



SPECIMEN NO. 129  
CONF. PRESS. = 0 PSI  
MAX. DIFF. STRESS = 2000 PSI  
STRAIN = 0.4 %



SPECIMEN NO. 76  
CONF. PRESS. = 10000 PSI  
MAX. DIFF. STRESS = 28000 PSI  
STRAIN = 20.5 %



SPECIMEN NO. 131  
CONF. PRESS. = 10000 PSI  
MAX. DIFF. STRESS = 32800 PSI  
STRAIN = 24.5 %

FIGURE 13  
AUSTIN CHALK SPECIMENS AFTER COMPRESSION  
AT VARIOUS CONFINING PRESSURES

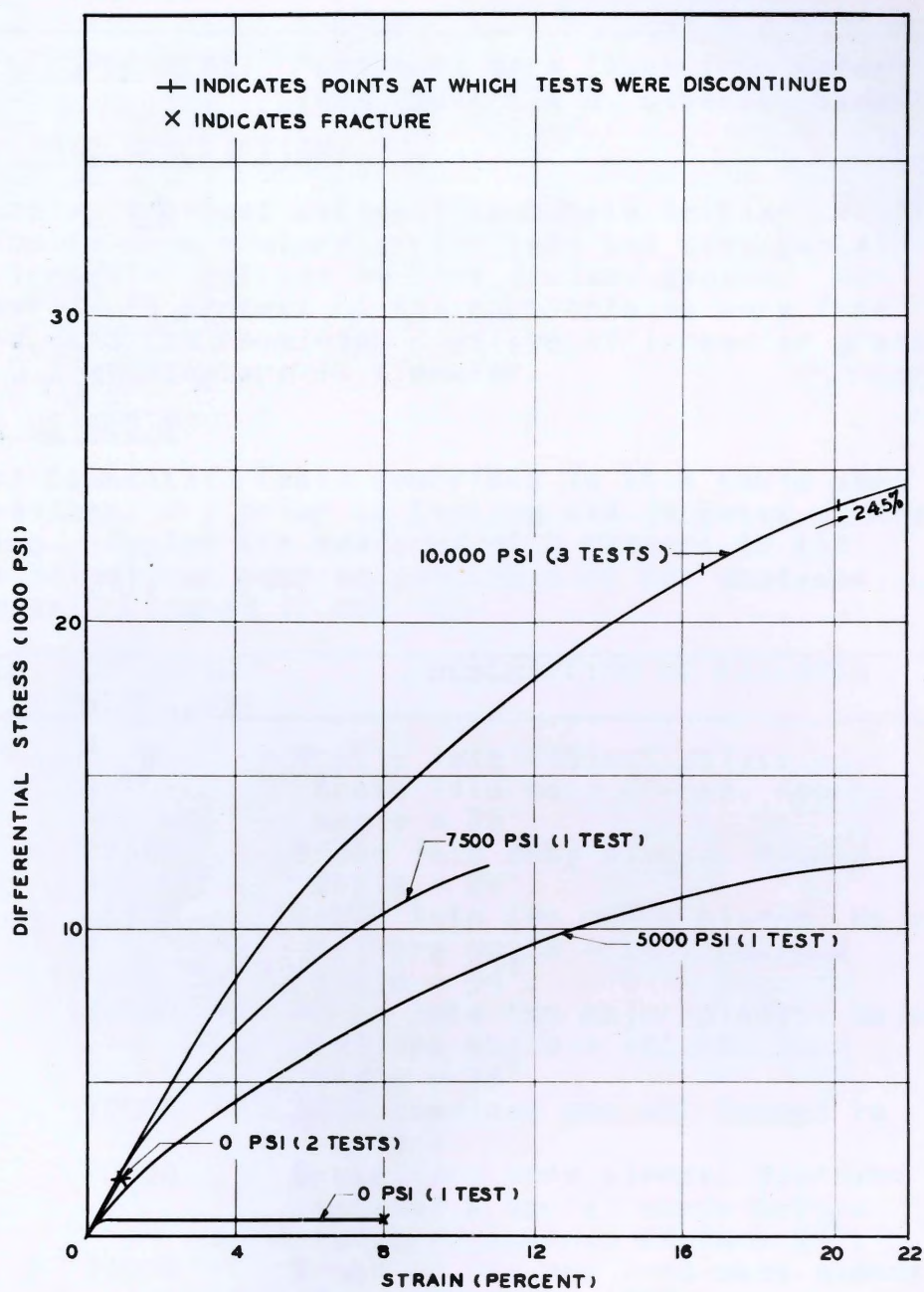


FIGURE 14  
STRESS-STRAIN CURVE OF AUSTIN CHALK TESTED IN  
COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE VI. D-1 FORMATION - PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from cores  
from Leduc Field, Elberta, Canada.

PETROGRAPHIC DESCRIPTION:

The sample is almost entirely carbonate (either calcite or dolomite or a mixture of the two) but does contain rare, irregular patches of fine grained gypsum. Approximately 95 percent of the carbonate is very fine grained, and the remainder consists of irregular grains up to 0.2 millimeters in diameter.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen.  
Reference: Figures 15 and 16.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
121	0	Mostly longitudinal splitting. Broke into many pieces. Approx. angle = 25°.
124	2500	Broke into many pieces. Approx. angle = 24°.
123	5000	Broke into two major pieces. Major failure angle = 24°. Maximum angle = 34°.
122	7500	Broke into two major pieces. Major failure angle = 18°. Maximum angle = 38°.
137	10000	This specimen was not loaded to failure.
159	10000	Broke into many pieces. Specimen assumed a barrel shape before failure. Approx. angle = 29°.
160	10000	Broke on one end into many pieces. Approx. angle = 30°.
138	15000	Broke into many pieces. Specimen assumed a barrel shape before failure. Approx. angle = 29°.





SPECIMEN NO. 121  
CONF. PRESS. = 0 PSI  
MAX. DIFF. STRESS = 23000 PSI  
STRAIN = 0.3%



SPECIMEN NO. 124  
CONF. PRESS. = 2500 PSI  
MAX. DIFF. STRESS = 29500 PSI  
STRAIN = 0.7%



SPECIMEN NO. 122  
CONF. PRESS. = 7500 PSI  
MAX. DIFF. STRESS = 73500 PSI  
STRAIN = 2.0%



SPECIMEN NO. 159  
CONF. PRESS. = 10000 PSI  
MAX. DIFF. STRESS = 63000 PSI  
STRAIN = 17.0%



SPECIMEN NO. 138  
CONF. PRESS. = 15000 PSI  
MAX. DIFF. STRESS = 89000 PSI  
STRAIN = 13.0%

FIGURE 15  
SPECIMENS FROM D-I FORMATION  
AFTER COMPRESSION AT VARIOUS CONFINING PRESSURES

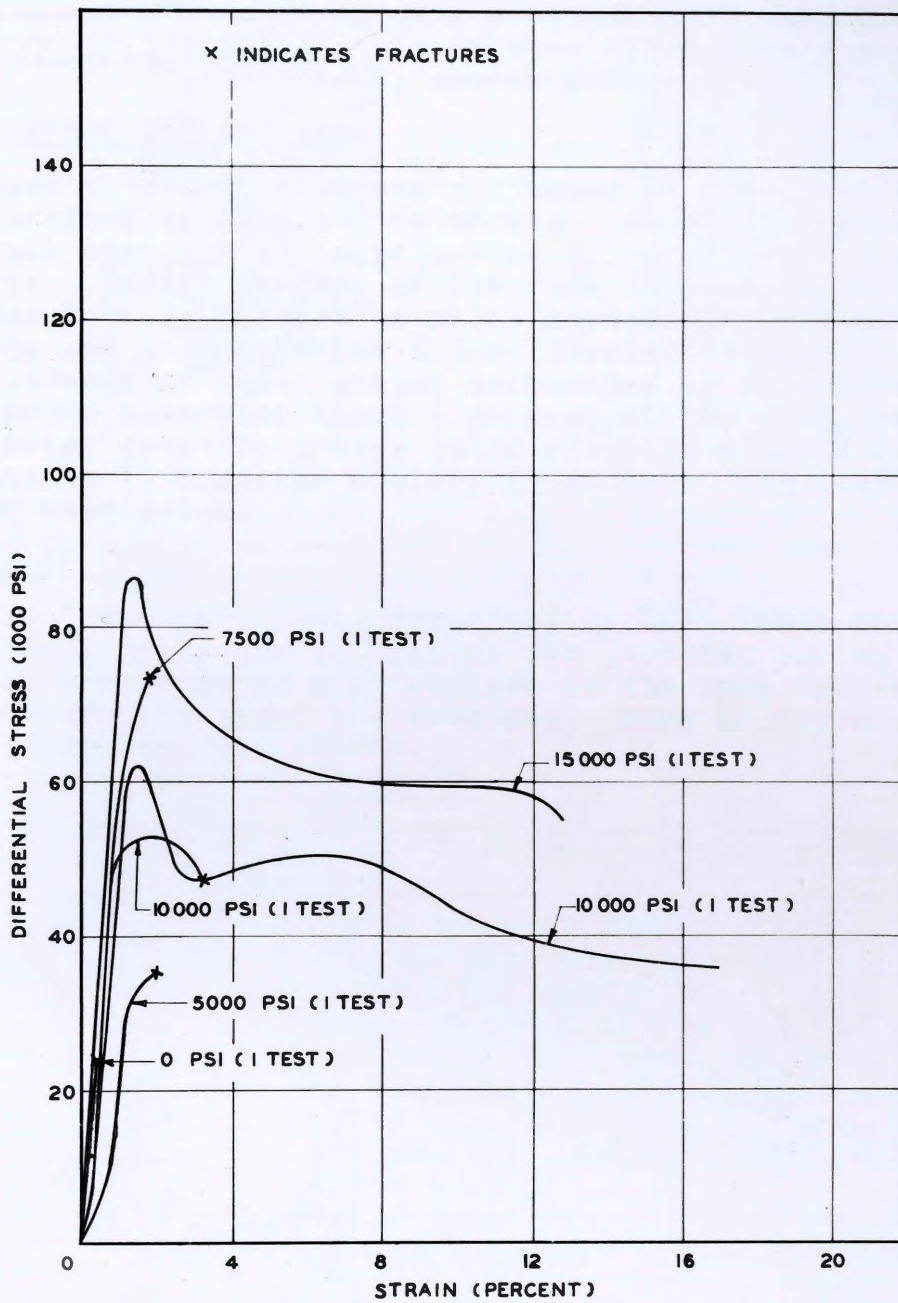


FIGURE 16  
STRESS-STRAIN CURVES OF D-1 FORMATION TESTED  
IN COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE VII. WHITE DOLOMITE - PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from quarried  
rock, source unknown.

PETROGRAPHIC DESCRIPTION:

The sample is most accurately classed as a serpentized forsterite-diopside-calcite marble. About 70 percent of the rock consists of interlocking 0.5-millimeter grains of calcite. Twenty percent of the rock is composed of fine grained fibrous serpentine which appears to replace the calcite and also cuts the 0.3-millimeter forsterite grains into islands of small grains surrounded by serpentine. Forsterite comprises about 5 percent of the rock, and 0.3-millimeter diopside grains (also slightly altered to serpentine ?) comprise another 5 percent. The minerals appear unoriented.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal or compression, axis of the specimen. None of these specimens remained intact.  
Reference: Figures 17 and 20.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
46	0	Mostly longitudinal splitting. Shear (?) surfaces are white and powdery. Angle = 29° approx.
57	0	Mostly longitudinal splitting. Very small shear (?) surfaces, showing white and powdery. Angle=29° Approx.
97	0	Mostly longitudinal splitting. Shear (?) surfaces are white and powdery. Angle = 32°.
98	0	Mostly longitudinal splitting. Shear (?) surfaces are white and powdery. Angle = 23° approx.
54	10000	Broke into two pieces. Shear (?) surfaces are white and powdery. Major failure angle=32°. Max. angle on end of specimen = 38°.
55	10000	Broke into two pieces. Shear (?) surfaces are white and powdery. Angle = 32°.
99	10000	Broke into two pieces. Shear (?) surfaces are white and powdery. Major failure angle=18°. Max. angle at end = 28°.
100	10000	Broke into two pieces. Shear (?) surfaces are white and powdery. Major failure angle = 27°. Max. angle at end = 30°.
101	15000	Broke into two pieces. Shear (?) surfaces are white and powder. Angle = 34°.





SPECIMEN NO. 57  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 10500 PSI  
 STRAIN = 0.8%



SPECIMEN NO. 97  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 9500 PSI  
 STRAIN = 0.7%



SPECIMEN NO. 100  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 51000 PSI  
 STRAIN = 1.3%



SPECIMEN NO. 101  
 CONF. PRESS. = 15000 PSI  
 MAX. DIFF. STRESS = 52000 PSI  
 STRAIN = 1.2%

FIGURE 17  
 WHITE DOLOMITE SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE VIII. VIRGINIA LIMESTONE - PETROGRAPHIC  
DESCRIPTION AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from rock  
quarried at Ripplemead, Virginia.

PETROGRAPHIC DESCRIPTION:

Almost 100 percent of the sample consists of very equigranular, 0.05-millimeter rhombs of carbonate; very slow effervescence in 6N HCl indicates that the carbonate is probably dolomite. Scattered through the rock are rare grains of coarse carbonate and fine grained quartz and feldspar. One section parallel to the length of the core contains a veinlet of medium-grained, rutilated (?) quartz grains.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen. None of these specimens remained intact.

Reference: Figures 18 and 19.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
40	0	Mostly longitudinal splitting into many pieces. Angle = 35° approx.
56	0	Longitudinal splitting into many pieces, some very thin slivers. Could not measure angle.
91	0	Longitudinal splitting into many pieces. Angle = 23° approx.
92	0	Longitudinal splitting into many pieces. Angle = 23° approx.
52	10000	Portion of one end failed at approx. 17° angle. This is specimen which appeared to flow (see Figure 19). Measurements do not indicate this to be the case.
53	10000	Broke into two major pieces. Major failure angle=18°. Max. angle at end = 28°.
93	10000	Broke into two major pieces. Major failure angle=18°. Max. angle at end = 41°.
94	10000	Broke into two major pieces. Major failure angle=16°. Max. angle at end = 35°.
95	15000	Broke in two major pieces. Major failure angle=21°.Max.at end=23-1/2°.





SPECIMEN NO. 91  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 31000 PSI  
 STRAIN = 0.9%



SPECIMEN NO. 93  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 113000 PSI  
 STRAIN = 1.5%



SPECIMEN NO. 95  
 CONF. PRESS = 15000 PSI  
 MAX. DIFF. STRESS = 125000 PSI  
 STRAIN = 1.5%

FIGURE 1B  
 VIRGINIA LIMESTONE SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

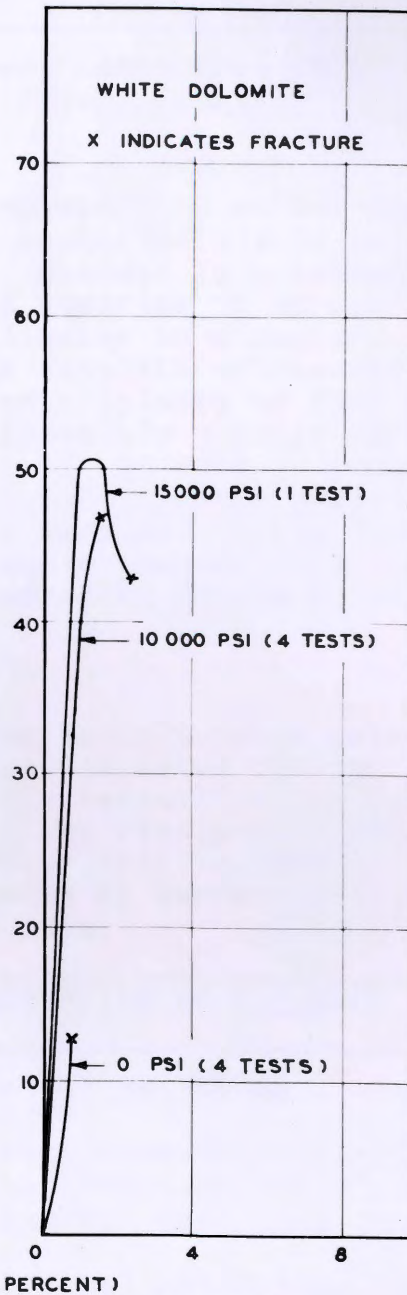
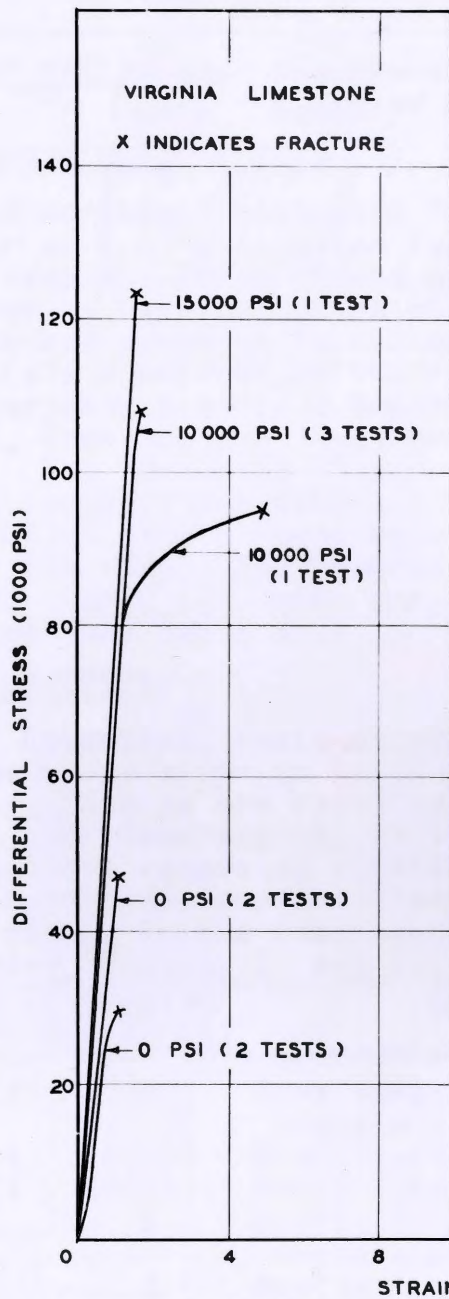


FIGURE 19  
STRESS-STRAIN CURVES OF ROCK SAMPLES TESTED  
IN COMPRESSION AT VARIOUS CONFINING PRESSURES

FIGURE 20

TABLE IX. FINE-GRAINED CHICO LIMESTONE -  
PETROGRAPHIC DESCRIPTION AND RESULTS  
OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from rock quarried at Chico, Texas.

PETROGRAPHIC DESCRIPTION:

Euhedral carbonate (dolomite ?) rhombs with an average diameter of 0.01 millimeter form approximately 50 percent of the sample. These rhombs are imbedded in a network of interlocking calcite grains which comprise 30 percent of the rock and range up to 0.1 millimeter in diameter. Approximately 5 percent of the rock consists of rounded, sub-spherical, 0.1- to 0.5-millimeter clasts of fine grained, iron-stained limestone (possibly altered foraminifera). The remaining 20 percent of the rock is composed of well rounded, sub-spherical, 0.2-millimeter grains of quartz which show a rough bedding parallel to the long axis of the core. The sheared sample (second core) contains no quartz and looks very much like coarse Chico limestone (see Table IV.).

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen. In cases of specimens remaining intact after testing, angles are those made by slip planes indicated by surface measured with respect to the compression axis.

Reference: Figures 21 and 22.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
65 Core 1	0	Some longitudinal splitting. Angle = $24-1/2^{\circ}$ .
66 Core 1	10000	Broke into two pieces. Angle = $24-1/2^{\circ}$ .
67 Core 1	10000	Broke into two pieces. Angle = $29^{\circ}$ .
115 Core 2	0	Mostly longitudinal splitting. Angle = $28^{\circ}$ .
116 Core 2	0	Mostly longitudinal splitting. Approx. angle = $28^{\circ}-31^{\circ}$ .
118A Core 2	7500	Specimen assumed barrel shape. Angle = $33^{\circ}$ .
117 Core 2	10000	Specimen assumed barrel shape. Angle = $34^{\circ}$ .
118 Core 2	10000	Specimen assumed barrel shape. Angle = $31^{\circ}$ .
117A Core 2	10000	Specimen assumed barrel shape. Angle = $34^{\circ}$ .





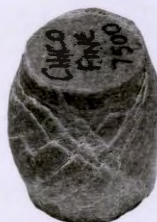
SPECIMEN NO. 65 CORE NO. 1  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 25000 PSI  
 STRAIN = 0.6%



SPECIMEN NO. 66 CORE NO. 1  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 64500 PSI  
 STRAIN = 1.4%



SPECIMEN NO. 115 CORE NO. 2  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 11000 PSI  
 STRAIN = 0.7%



SPECIMEN NO. 118A CORE NO. 2  
 CONF. PRESS. = 7500 PSI  
 MAX. DIFF. STRESS = 33000 PSI  
 STRAIN = 27%



SPECIMEN NO. 117 CORE NO. 2  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 38000 PSI  
 STRAIN = 19.5%

FIGURE 21

FINE CHICO LIMESTONE SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

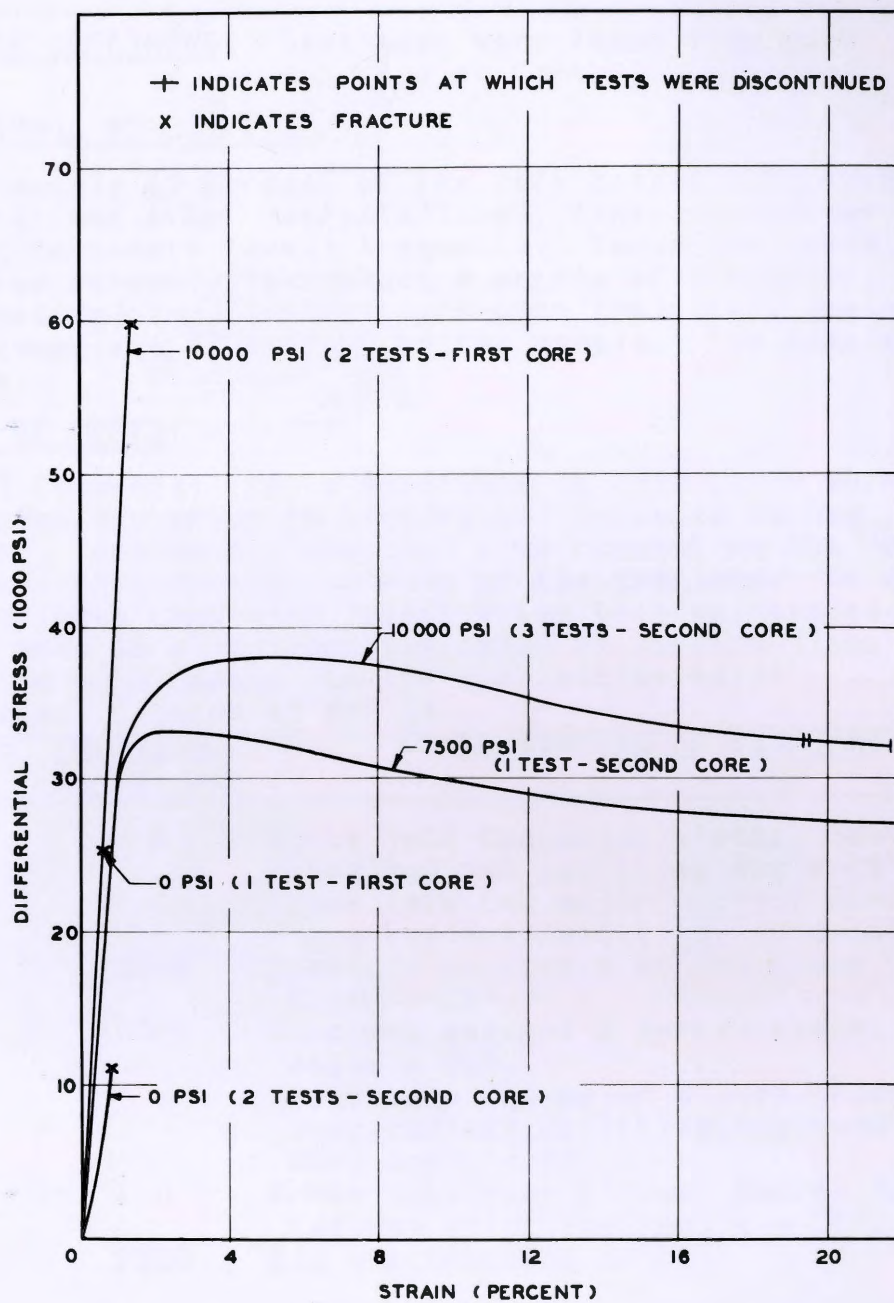


FIGURE 22

STRESS - STRAIN CURVES OF FINE CHICO LIMESTONE  
 TESTED IN COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE X. CARTHAGE MARBLE - PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from rock  
quarried at Carthage, Missouri.

PETROGRAPHIC DESCRIPTION:

Approximately 40 percent of the rock consists of foraminiferal and other recrystallized, fine- or coarse-grained carbonate fossil fragments. These fragments are scattered randomly throughout a matrix of irregular, interlocking, 1-millimeter carbonate (calcite?) grains which comprises 60 percent of the sample. The sample is massive.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen. In cases of specimens remaining intact after testing, angles are those made by slip lines indicated by surface lines measured with respect to the compression axis.

Reference: Figures 23 and 24.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
61 Core 1	0	Broke into two major pieces. Some longitudinal splitting. Angle=26°.
62 Core 1	0	Broke into two major pieces. Some longitudinal splitting. Angle=26°.
63 Core 1	10000	Specimen assumed a barrel shape. Angle = 26°.
64 Core 1	10000	Specimen assumed a barrel shape. Angle = 36°.
109 Core 2	0	Broke into two major pieces. Some longitudinal splitting. Angle=18°. Max. angle = 30°.
110 Core 2	0	Broke into many pieces. Mostly longitudinal splitting. Angle = 26°.
114 Core 2	2500	Did not fracture in test.
113 Core 2	5000	Did not break in test. Angle (surface) = 36°.
112 Core 2	7500	Specimen assumed a barrel shape. Angle = 36°.
111 Core 2	10000	Specimen assumed a barrel shape. Angle = 36°.

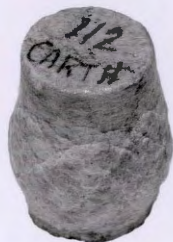




SPECIMEN NO. 61 CORE NO. 1  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 13000 PSI  
 STRAIN = 0.3 %



SPECIMEN NO. 113 CORE NO. 2  
 CONF. PRESS. = 5000 PSI  
 MAX. DIFF. STRESS = 27000 PSI  
 STRAIN = 0.5 %



SPECIMEN NO. 112 CORE NO. 2  
 CONF. PRESS. = 7500 PSI  
 MAX. DIFF. STRESS = 28500 PSI  
 STRAIN = 21.5 %



SPECIMEN NO. 111 CORE NO. 2  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 31500 PSI  
 STRAIN = 11.0 %

FIGURE 23  
 CARTHAGE MARBLE SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

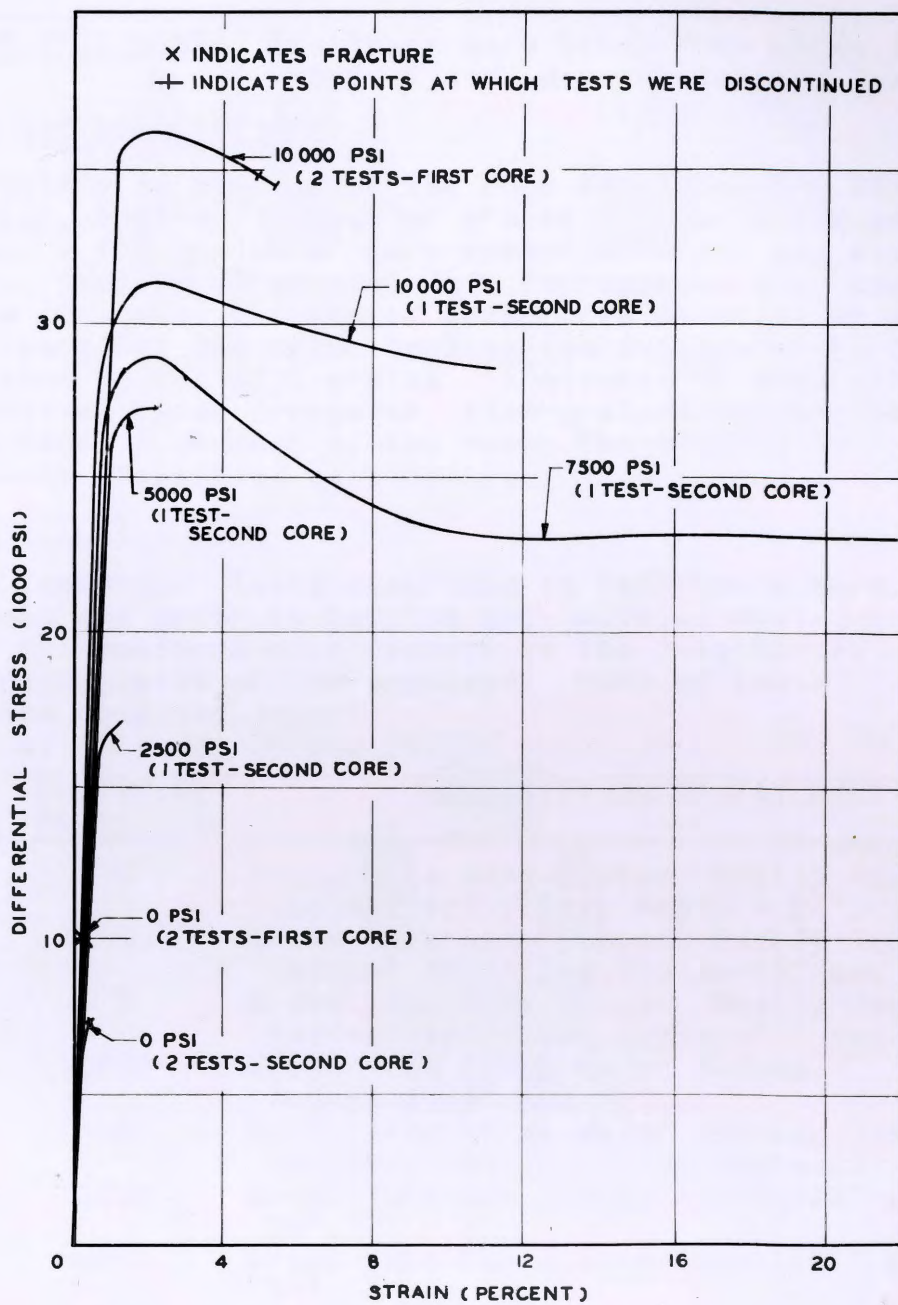


FIGURE 24

STRESS-STRAIN CURVES OF CARTHAGE MARBLE TESTED  
IN COMPRESSION AT VARIOUS CONFINING PRESSURES



TABLE XI. WYOMING RED BED - PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from cores from  
Sussex Field, Johnson County, Wyoming.

PETROGRAPHIC DESCRIPTION:

Approximately 30 percent of the rock consists of 0.05-millimeter, angular, irregular grains of quartz and some feldspar; a few grains of dark opaque minerals are also present. Another 65 percent is a ferruginous clay containing some irregular streaks of darker red material which roughly parallel the crude bedding (perpendicular to the core) shown by the silt grains. A mineral of moderate birefringence forms irregular, fine-grained patches which make up about 5 percent of the rock; the mineral is tentatively identified as anhydrite.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen. None of these specimens remained intact.

Reference: Figures 25 and 26.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
41	0	Broke into many pieces. Mostly longitudinal splitting. Angle = 24°.
42	0	Broke into many pieces. Mostly longitudinal splitting. Angles=25° and 16°.
82	0	Broke into many pieces. Mostly longitudinal splitting. Angles=23° and 26°.
48	10000	Broke into three major pieces. Angles = 23° and 33°.
49	10000	Broke into three major pieces. Some longitudinal splitting. Angle=25°.
83	10000	Broke into two pieces. Angles=28° and 29°.
84	10000	Broke into two pieces. Angles=21° and 33°.
135	15000	Barreled on one end before fracture. Angle = 35°.



SPECIMEN NO. 82  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 23000 PSI  
 STRAIN = 0.9%

SPECIMEN NO. 83  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 55000 PSI  
 STRAIN = 22 %



SPECIMEN NO. 135  
 CONF. PRESS. = 15000 PSI  
 MAX. DIFF. STRESS = 65000 PSI  
 STRAIN = 17.0 %

FIGURE 25  
 WYOMING RED BED SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

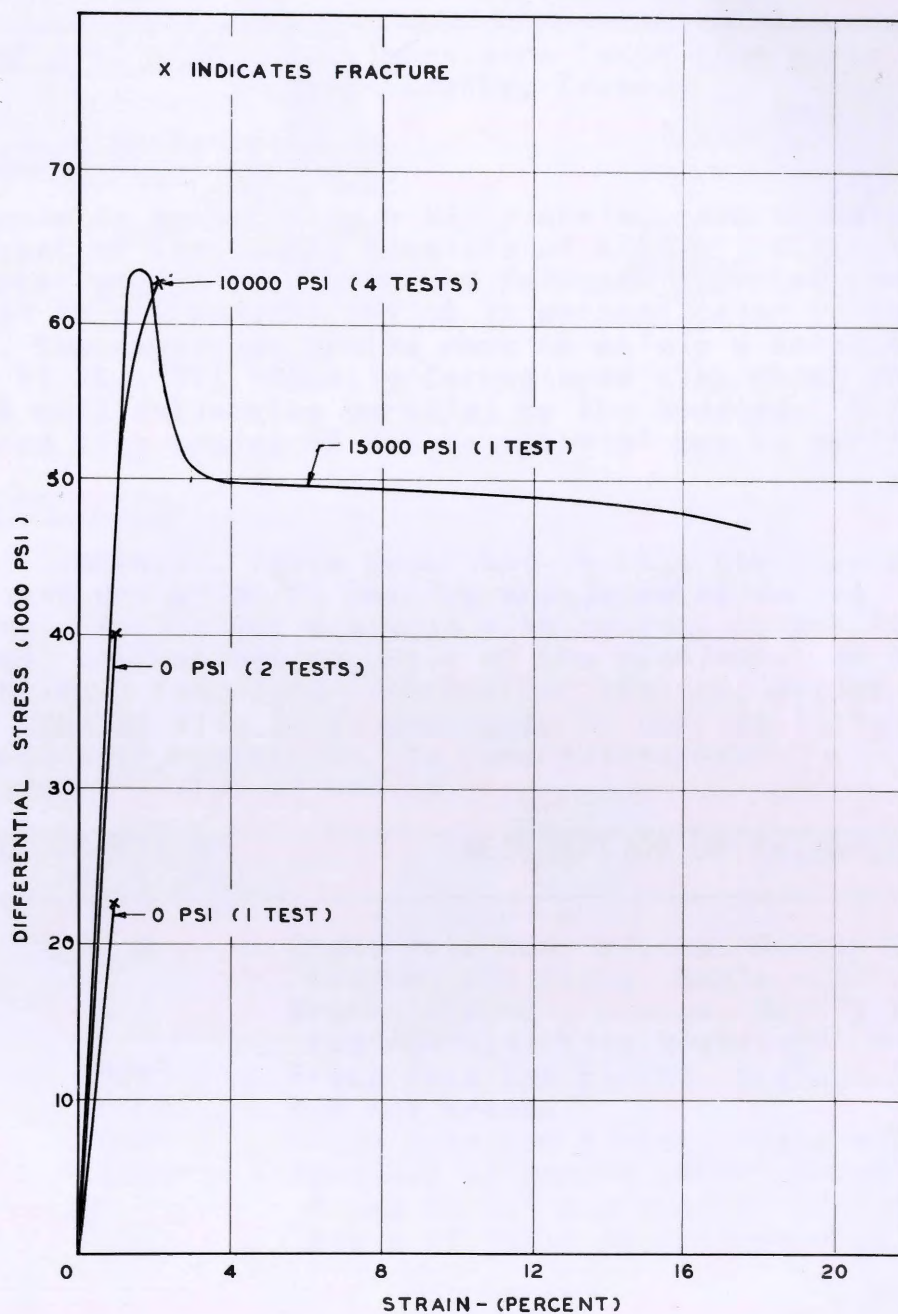


FIGURE 26

STRESS-STRAIN CURVES OF WYOMING RED BED TESTED  
IN COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE XII. SHALE - PETROGRAPHIC DESCRIPTION AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from cores from Duval County, Texas.

PETROGRAPHIC DESCRIPTION:

The sample is essentially a silty shale. Approximately 40 percent of the sample consists of angular, 0.02-millimeter grains of quartz and feldspar oriented roughly parallel to the bedding (which is perpendicular to the core). The remainder of the rock is mainly a carbonaceous, illitic (?) slightly ferruginous clay which shows a rough unit extinction parallel to the bedding. A few scattered tiny grains of opaque material may be pyrite.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens dry prior to testing and jacketed during testing. Angles are measured with respect to the longitudinal, or compression, axis of the specimen. In cases of specimens remaining intact after testing, angles are those made by slip lines indicated by surface lines measured with respect to the compression axis.

Reference: Figures 27 and 28.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
72	0	Broke into many pieces. Mostly longitudinal splitting. Angle = 17°.
73	0	Broke into many pieces. Mostly longitudinal splitting. Angles = 23° and 15°.
78	10000	Broke into two pieces. Angle = 30°.
79	10000	Did not break.
80	10000	Broke into two pieces. Angle = 38°.
139	15000	Specimen assumed a barrel shape. Broke on 32° angle after testing. Angle of lines on surface = 38°.





SPECIMEN NO. 73  
 CONF. PRESS. = 0 PSI  
 MAX. DIFF. STRESS = 14500 PSI  
 STRAIN = 11%



SPECIMEN NO. 80  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 36000 PSI  
 STRAIN = 2.5%



SPECIMEN NO. 139  
 CONF. PRESS. = 15000 PSI  
 MAX. DIFF. STRESS = 46000 PSI  
 STRAIN = 19.5%

FIGURE 27  
 SHALE SPECIMENS AFTER COMPRESSION  
 AT VARIOUS CONFINING PRESSURES

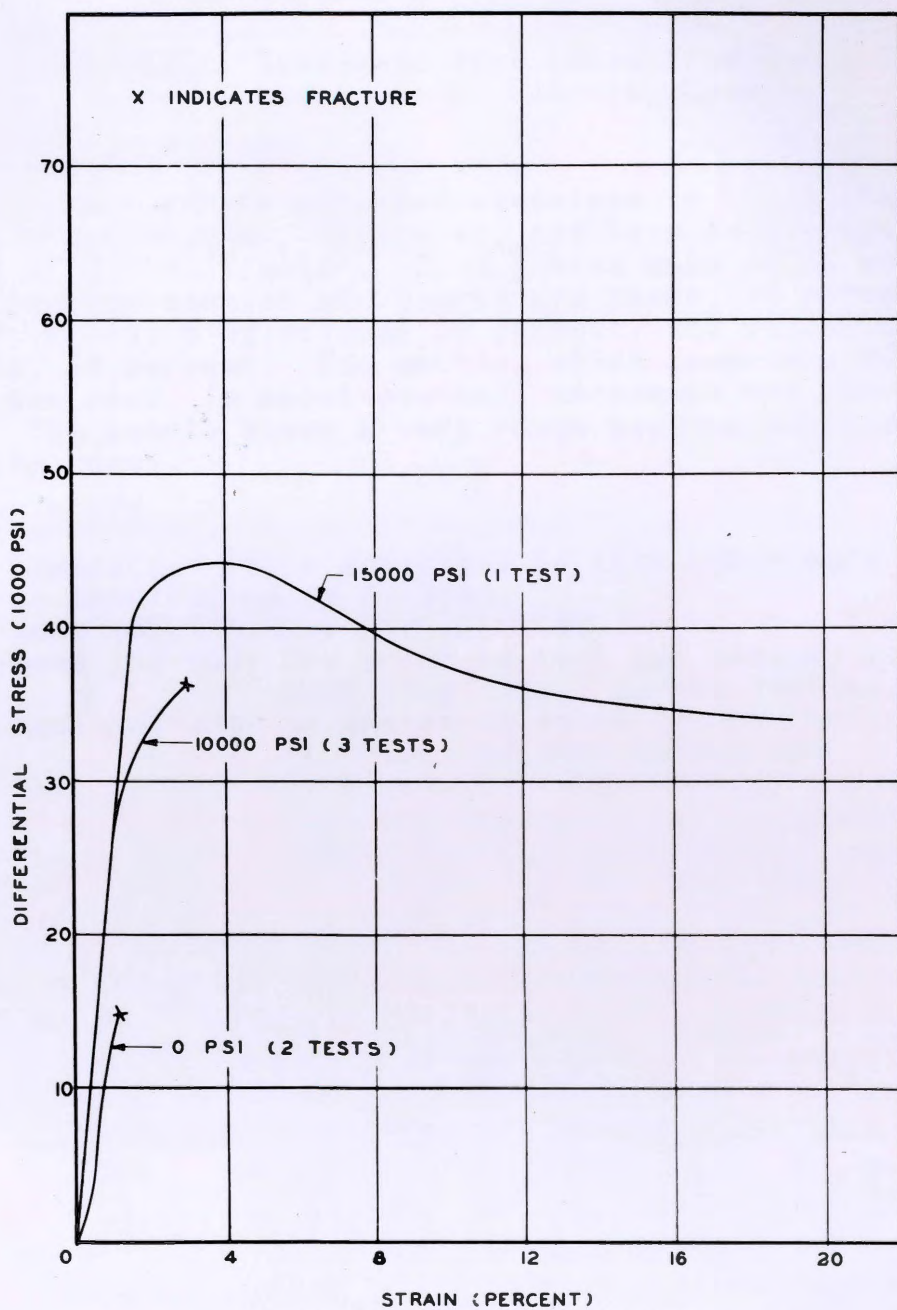


FIGURE 28  
STRESS-STRAIN CURVES OF SHALE TESTED IN  
COMPRESSION AT VARIOUS CONFINING PRESSURES

TABLE XIII. SANDY SHALE - PETROGRAPHIC DESCRIPTION  
AND RESULTS OF TESTS.

SOURCE OF SPECIMENS: Specimens were taken from cores from Leduc Field, Elberta, Canada.

PETROGRAPHIC DESCRIPTION:

The rock is a moderately sorted sandstone in which the sand grains are sub-angular, irregular, and have an average diameter of 0.2-millimeter. Sand grains make up 70 percent of the rock and consist of: quartz and chert, 70 percent; feldspar (mainly plagioclase) 20 percent; and volcanic fragments, 10 percent. The matrix, which comprises 30 percent of the rock, is about one-half carbonate and one-half silica. The sample shows a very rough bedding perpendicular to the core.

RESULTS OF TESTS:

General Comments: Tests described in this table were on specimens conditioned as follows:

Specimens 145-150: Dry and jacketed.

Specimens 157-158: Dry prior to test but exposed to the confining liquid during testing.

Specimens 142-144: Saturated in water 72 hrs. prior to test and jacketed during test.

Specimens 151-156: Saturated in water 72 hrs. prior to test and exposed to the confining liquid during test.

Angles are measured with respect to the longitudinal, or compression axis, of the specimen. In cases of specimens remaining intact after testing, angles are those made by slip lines indicated by surface lines measured with respect to the compression axis.

Reference: Figures 29, 30, 31, and 32.

SPECIMEN	CONFINING PRESS., PSI.	DESCRIPTION OF FAILURES
145	0	Broke into two major pieces. Angle=22°.
146	0	Broke into two major pieces. Angle=24°.
147	5000	Specimen assumed a barrel shape. Angle = 37°.
148	5000	Specimen assumed a barrel shape. Angle = 35°.
149	10000	Specimen assumed a barrel shape. Angle = 37°.
150	10000	Specimen assumed a barrel shape. Angle = 45°.
158	5000	Broke into two major pieces. Some longitudinal splitting. Angle = 38°.
157	10000	Broke into two major pieces. Angle=48°.
144	5000	Specimen barreled predominantly on end. Non-barreled end broke off into disk. Angle = 41°.
142	10000	Broke into six disks of approx. equal thickness, all failures on planes perpendicular to axis of compression.
143	10000	Broke into five disks of approx. equal thickness, all failures on planes perpendicular to axis of compression.
156	0	Broke into two major pieces. Numerous small pieces, some crumbling. Angle = 21°.
155	0	Broke into two major pieces. Angle=21°.
154	5000	Broke into two pieces. Angle = 21°.
153	5000	Broke into four pieces. Angle=26°.
152	10000	Broke into two major pieces. Angle=25°.
151	10000	Broke into two pieces. Major failure angle=22°. Max. angle = 38°.





SPECIMEN NO. 146  
CONF. PRESS. = 0 PSI  
MAX. DIFF. STRESS = 6500 PSI  
STRAIN = 1.2%



SPECIMEN NO. 147  
CONF. PRESS. = 5000 PSI  
MAX. DIFF. STRESS = 23000 PSI  
STRAIN = 20.0%



SPECIMEN NO. 149  
CONF. PRESS. = 10000 PSI  
MAX. DIFF. STRESS = 32500 PSI  
STRAIN = 26.0%

NOTE: THESE SPECIMENS WERE DRY AND JACKETED. SEE FIGURE 31



SPECIMEN NO. 158  
CONF. PRESS. = 5000 PSI  
MAX. DIFF. STRESS = 22500 PSI  
STRAIN = 1.0%



SPECIMEN NO. 157  
CONF. PRESS. = 10000 PSI  
MAX. DIFF. STRESS = 17000 PSI  
STRAIN = 1.1%

NOTE: THESE SPECIMENS WERE DRY BEFORE TESTING BUT EXPOSED DURING TESTING. SEE FIGURE 32, NOTE 2

FIGURE 29  
DRY SANDY SHALE SPECIMENS AFTER  
COMPRESSION AT VARIOUS CONFINING PRESSURES





SPECIMEN NO. 144  
 CONF. PRESS. = 5000 PSI  
 MAX. DIFF. STRESS = 17000 PSI  
 STRAIN = 29.0 %



SPECIMEN NO. 142  
 CONF. PRESS. = 10000 PSI  
 MAX. DIFF. STRESS = 22000 PSI  
 STRAIN = 18.5 %

NOTE: THESE SPECIMENS WERE SATURATED AND JACKETED. SEE FIGURE 32, NOTE 1



SPECIMEN NO. 154  
 CONF. PRESS. = 5000 PSI  
 MAX. DIFF. STRESS = 6500 PSI  
 STRAIN = 1.0 %

NOTE: SPECIMEN TYPICAL OF ALL SATURATED AND EXPOSED SPECIMENS AT 0:5000:  
 AND 10000 PSI CONFINING PRESSURES. SEE FIGURE 32, NOTE 3

FIGURE 30  
 SATURATED SANDY SHALE SPECIMENS AFTER  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

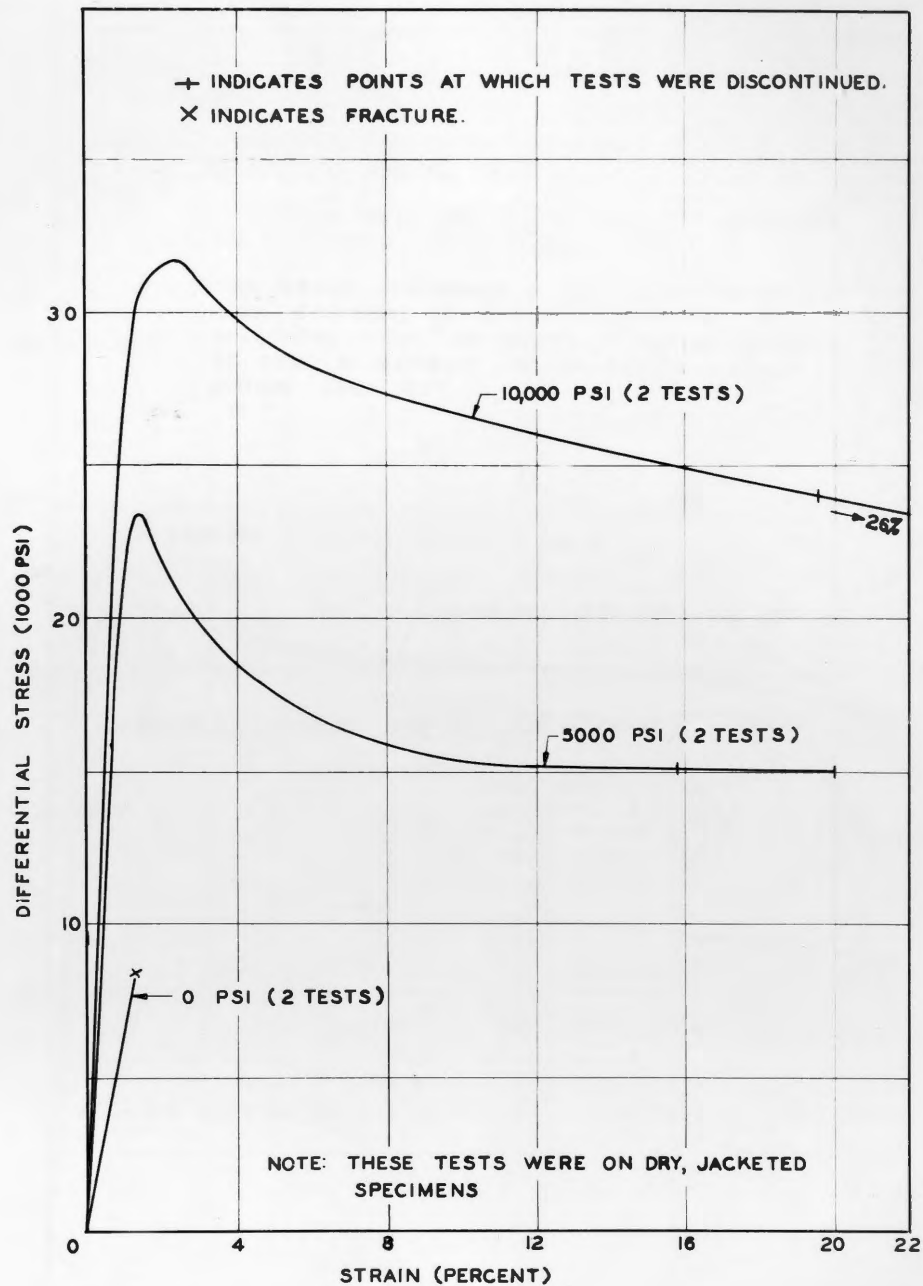


FIGURE 31  
 STRESS-STRAIN CURVES OF SANDY SHALE TESTED IN  
 COMPRESSION AT VARIOUS CONFINING PRESSURES

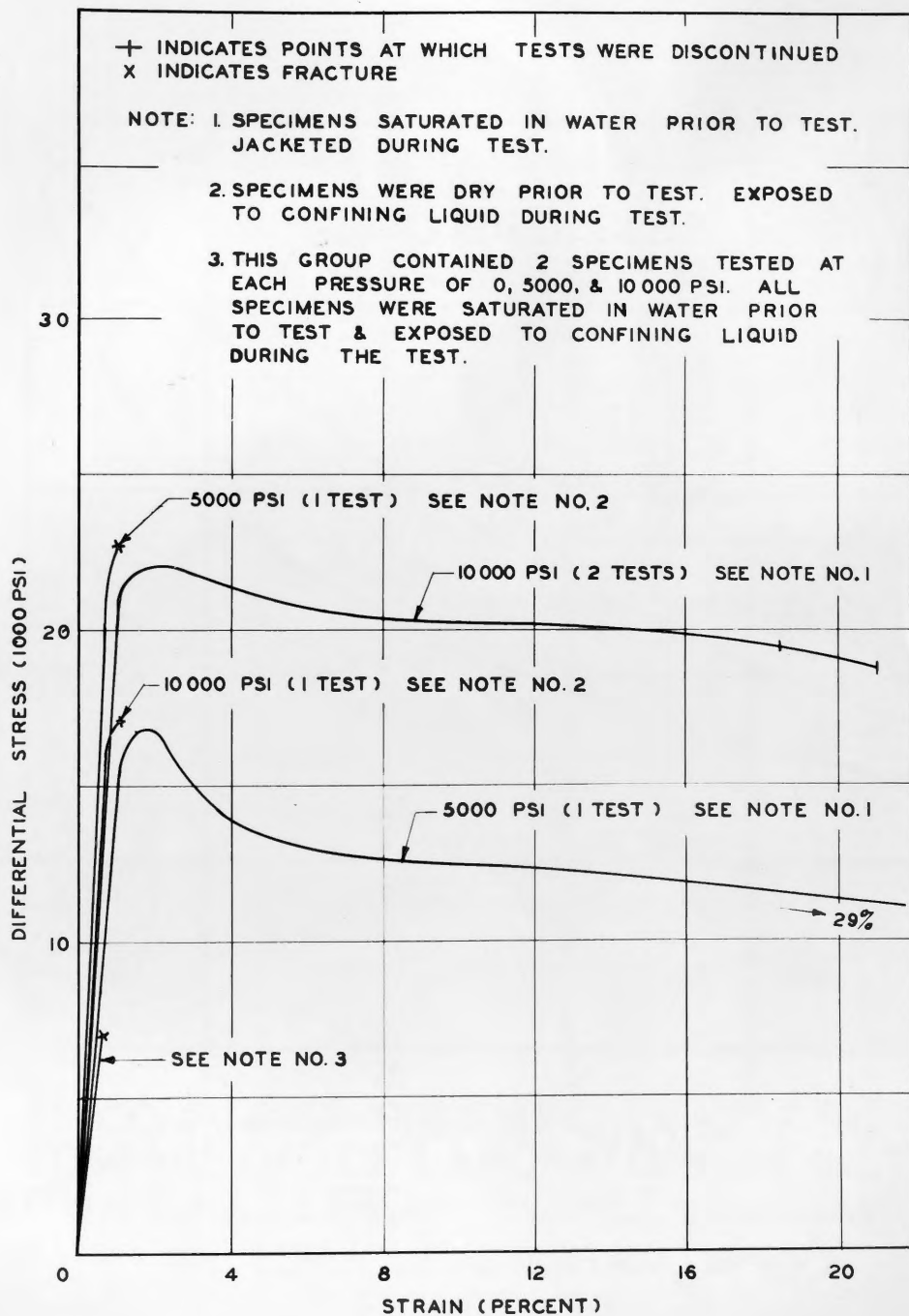
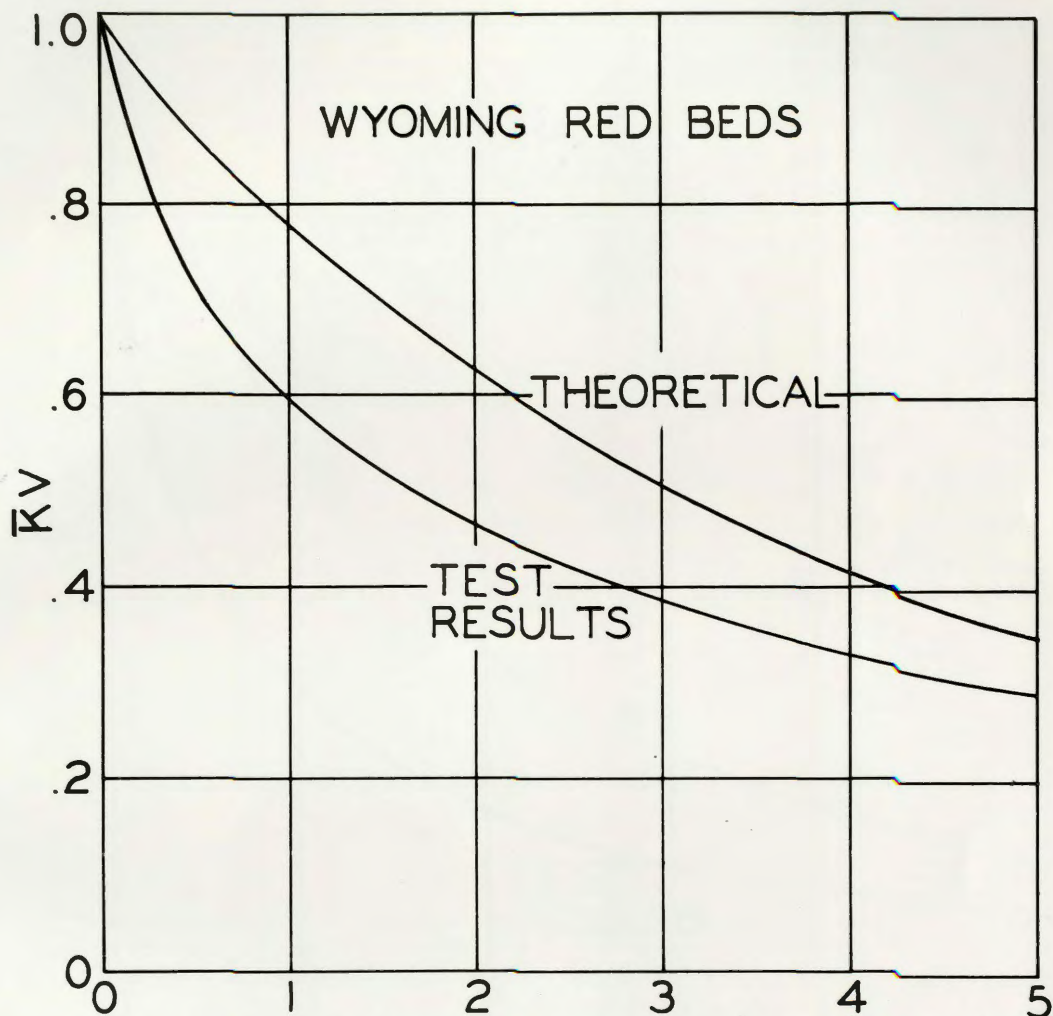


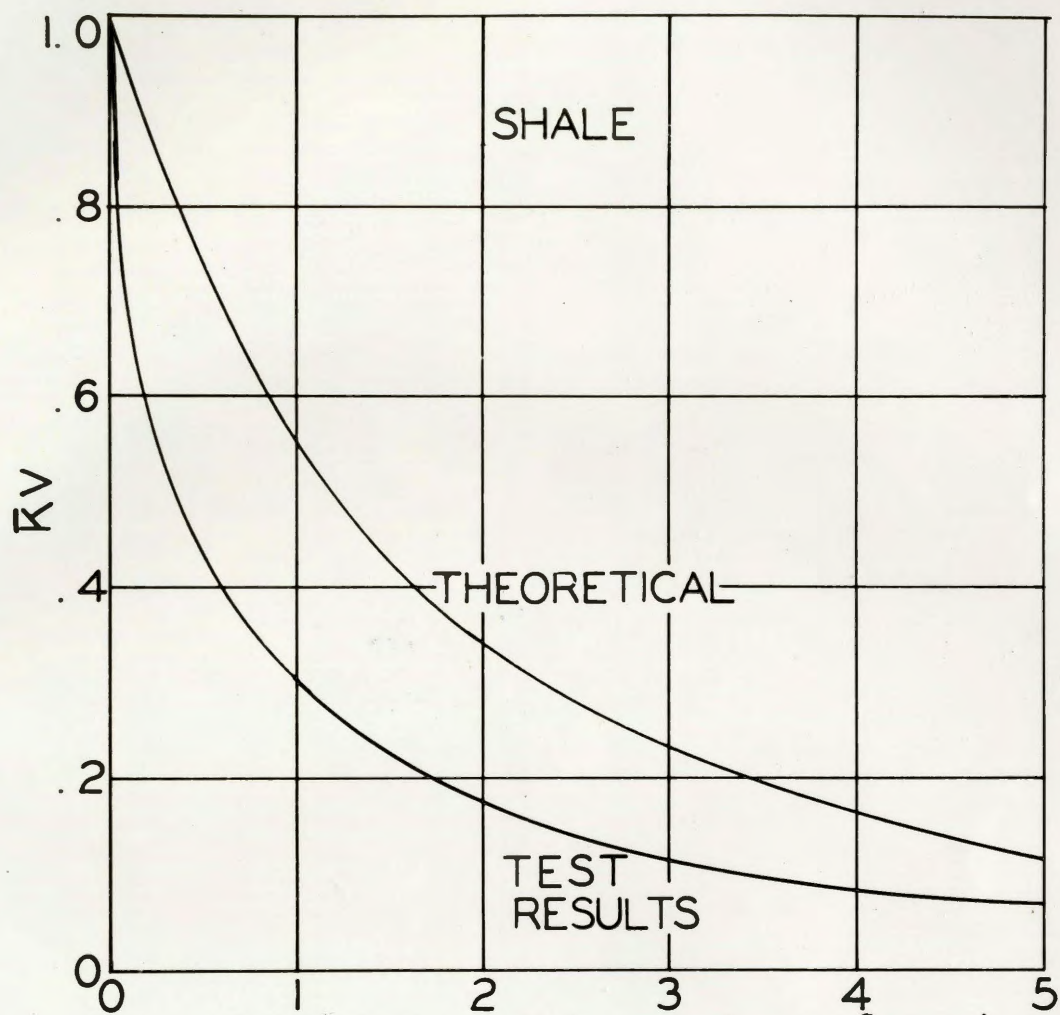
FIGURE 32

STRESS-STRAIN CURVES OF SANDY SHALE TESTED  
IN COMPRESSION AT VARIOUS CONFINING PRESSURES



WYOMING RED BEDS  
 THEORETICAL  
 TEST RESULTS  
 KV  
 CONFINING PRESSURE ( $\times 10^3$  PSI)  
 COMPARISON OF LABORATORY RESULTS  
 WITH RESULTS FROM THEORETICAL EQUATIONS  
 (AFTER CUNNINGHAM, 1955)  
 FIGURE 33





COMPARISON OF LABORATORY RESULTS  
WITH RESULTS FROM THEORETICAL EQUATIONS  
(AFTER CUNNINGHAM, 1955)  
FIGURE 34